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Great Plains Regional Center

William E. Easterling, Director

The Great Plains Regional Center (GPRC) began its second year of operation in 1994. Situated in the Institute of Agriculture and Natural Resources at the University of Nebraska-Lincoln, the GPRC is administered by Director William E. Easterling, Associate Director Blaine L. Blad and Project Assistant Jan Schinstock. The GPRC office is located in the Department of Agricultural Meteorology where the Director and Associate Director maintain academic appointments.

The GPRC focuses on the region encompassed by the states of Iowa, Kansas, Minnesota, Missouri, Montana, Nebraska, North and South Dakota and Wyoming. Colorado is shared with the South Central Regional Center. Research pertaining to the southern Great Plains (Oklahoma, Texas, New Mexico) is of relevance to the GPRC, but is coordinated with the South Central Regional Center.

The Great Plains region encompasses the nation's largest grassland biome. The region produces nearly a quarter of the nation's agricultural crops and livestock. Also, it is typified by strong climatic gradients, with annual precipitation of over 900 mm on the eastern edge to less than 200 mm on the western edge. Its interior continental position produces large interseasonal extremes of temperature and precipitation, and the frequency of extreme events, especially droughts, is higher in the Great Plains than in regions nearer large water bodies. Agriculture and other ecosystems in the region are known to respond nonlinearly to climate forcing. Small changes in already marginal climate conditions for many ecosystems produce disproportionately large impacts. The deep loess soils typical of the Great Plains store large amounts of carbon in the form of soil organic matter. Moreover, observed changes in the composition and location of ecotones, changes in the extent and intensity of land use, coupled with periodic climate variations have strongly influenced the cycling of nutrients and net exchanges of carbon in the Great Plains. Finally, several climate models predict severe climate changes in mid-latitude continental interiors relative to global average changes. These above factors argue for a research program that focuses on the potential consequences of climate change for the Great Plains region.

The remainder of this report will: (1) summarize the conceptual framework of the GPRC's research program and corresponding research thrusts; (2) summarize the FY94 grant competition and provide a synopsis of all projects funded in 1994, organized by research thrust; (3) summarize important outcomes of the 1994 first annual GPRC PIs workshop and other activities aimed at research integration; and (4) outline future activities of the GPRC. Appended to this report are the detailed FY 94 progress reports for each of the projects funded by the GPRC.

GPRC RESEARCH FRAMEWORK AND THRUSTS

The primary goal of the GPRC is to develop a "bottom-up" regional research program that provides basic understanding of the implications of climate change for the Great Plains to complement the efforts of the U.S. Department of Energy to develop integrated assessment policy tools. The term bottom-up is defined here as research that begins *in situ* at the process level and, through scaling and aggregation of results, is extrapolated to derive regional estimates of response to environmental forcing. The regional estimates are meant to be comparable across NIGEC regions. The research scope of the GPRC will be "end-to-end," identifying and, where possible, quantifying explicit linkages between climate change, basic biophysical and ecological processes (e.g., hydrologic properties, plant physiology and water relations, surface energy exchanges), managed and unmanaged ecosystem function (e.g., biogeochemical cycling, net primary productivity, adaptive capacity), and socioeconomic activity (impacts on gross regional product and net social welfare, institutional response) including feedback mechanisms (e.g., climate change-induced changes in landuse and corresponding land-cover with feedbacks to soil organic matter and trace gas emissions). As such, the GPRC research program will provide an alternative to reduced-form climate

change damage functions for estimating the impacts of climate change within integrated assessment models.

The major components of the GPRC's research program are shown schematically on figure 1. The figure begins with the development of appropriate regional scenarios of climate change leading to process studies and regional estimates of net carbon exchanges between the atmosphere and the region's managed and unmanaged ecosystems; the chain of causality also leads from climate change scenarios and process studies to the estimation of impacts on those ecosystems and ends with an economic assessment of the regional consequences of climate change and efforts to adapt to and mitigate such change. Land use change is seen as linking adaptation with processes of net carbon exchange. Methodological research such as, for example, development of techniques for scaling and aggregation of model results, is embedded throughout the framework.

The above framework was the foundation for the 1994 GPRC research thrusts which, in summary form, were: (1) *the quantification of the consequences of climate change for managed and unmanaged ecosystems of importance to human activity in grasslands, including assessment of the adaptive capacity of such ecosystems and feedbacks, if any, to the next thrust; and (2) the measurement and modeling of net exchanges of carbon dioxide and other energy-relevant radiatively-active trace gases between terrestrial ecosystems and the atmosphere, particularly in grasslands.* An additional research thrust focusing on the detection and attribution of greenhouse-forced climate change was deleted last year, although final reports from projects addressing that thrust are included in this year's set.

FY94 GPRC GRANT COMPETITION

The GPRC conducted its second grant competition over the fall-winter of 1993-94 in order to allocate research funds for FY94. Funds for new projects were extremely limited since most of the GPRC's projects were begun the previous year. Thirty-two proposals were received from twenty institutions in or near the Great Plains region. Fourteen of these proposals were second- or third-year continuation proposals. Of the remaining eighteen new proposals submitted, four were funded. All proposals received were peer reviewed by mail and by a scientific advisory panel for scientific merit and were submitted to DOE for a test of relevancy to agency research priorities. Research money was awarded to eighteen proposals, with approximately 36% of the funds going to University of Nebraska-Lincoln (UN-L) investigators and 64% going to investigators at other institutions.

The total allocation of research funds to the 18 projects was \$1,467,300, leaving \$38,001 in the Director's Fund for FY94. The Director's Fund was used to: (1) conduct the 1994 GPRC Pls Workshop in Lincoln (summarized below); (2) to fund a seed project by J. Antle of Montana State University to develop an economic modeling framework to be expanded into a major integrated assessment proposal for FY96; and (3) to support a meeting of GPRC investigators to coordinate development of alternative scenarios of climate change for impact analysis.

SYNOPSIS OF CURRENT PROJECTS

A brief synopsis of current projects is divided into the two research thrusts of the GPRC. Some projects overlap thrusts and are discussed accordingly. All projects discussed below are described in detail in the progress reports that follow. Unless otherwise noted, all projects discussed below received initial actual funding in December of 1993—thus, progress reported was for 18 months of work.

Thrust 1: Impacts of Climate Change

Process Studies. Field-based process studies are being conducted better to understand basic interactions of climate with physical and biological systems in the Great Plains. Such understanding will, in some cases, provide better model constructs for estimating impacts of climate change. In their second year of a three-year project, Blair and colleagues at Kansas State University are examining the effects of altered

soil moisture and temperature on basic biological properties of and processes in prairie soils (e.g., soil organisms, organic matter storage and turnover, nutrient retention) by reciprocal transplanting of intact soil cores between different climate regimes to then study soil response to the new climate. *An important result to date is the observed rapid decline of potentially mineralizable nitrogen in xeric soils transported to relatively more humid climates.*

In their second year of a three-year project, Rundquist and colleagues at the University of Nebraska-Lincoln are studying highly dynamic lake/wetland systems in the Nebraska Sand Hills to establish baseline conditions (e.g., relationships between climate, groundwater and biomass, and energy and carbon fluxes), against which "environmental variance" can be determined using a combination of *in situ* climate and hydrologic data and remote sensing imagery (Landsat-TM and MSS). Linkage of imagery of biomass with trace gas fluxes in prairie wetlands being measured by Verma and colleagues (reported below) is also being attempted. *An important result to date is the development of relationships between changes in remotely-sensed lake surface area, the timing of precipitation and interseasonal rates of evapotranspiration. Some results of area measurements, for 130 lakes from 42 Landsat-MSS scenes over 15 years, include mean sizes that range from <5 to 870 acres and standard deviations that range from 3 to 60 acres. The investigators have documented the fact that the lakes and the groundwater systems function in concert with one another.*

In their second year of a two-year project (with a proposed three-year follow-on study under development), Hoagland and colleagues at the University of Nebraska-Lincoln are studying genetic markers among diatom floras along a zonal temperature gradient in the Great Plains to understand the adaptability of such species to different climate regimes in order to understand how climate change may affect prairie aquatic systems¹. *An important result to date has been the success in separating distinct diatom clones by location along the latitudinal transect. These observed clusters are confirmations of laboratory temperature manipulations. Temperature ranges for optimal growth of different clones were established.*

Climate Scenarios for Impacts analysis. Alternative methodologies for the development of climate change scenarios for use in the conduct of impact analyses are an important component of Thrust 1. Based on recommendations from the first annual PIs workshop, the GPRC is coordinating an intercomparison of climate scenario generation techniques. Scenarios generated by a small selection of those techniques are being coordinated by the GPRC for distribution to other GPRC projects to use in estimating climate change impacts.

In the second year of a three-year study, Mearns and colleagues at the National Center for Atmospheric Research and the University of Nebraska-Lincoln are developing and manipulating regional climate models "nested" within general circulation models (GCMs) to produce high-resolution climate change scenarios in order to test the importance of spatial and temporal scale in estimating the agricultural impacts of climate change. *Important results to date include the successful replication of the 1988 summer precipitation anomaly in the interior U.S. with the nested climate model and the finding that resolving climate data inputs at smaller grid box scales than GCMs vastly improve agreement between modeled estimates of crop yields and observed crop yields, although highly resolved soil data inputs do not seem to matter.*

In the second year of a three-year study, Palecki and colleagues at the University of Nebraska-Lincoln, University of Delaware and Rutgers University are using a "calendar shift" method to generate climate warming scenarios. By shifting each month either forward or backward, depending on the natural seasonal progression of warming/cooling, they have developed a new monthly distribution of daily temperatures and precipitation. A water balance model is being computed with the seasonally-adjusted climate to examine impacts of such climate scenarios. *An important result to date has been the demonstrated close*

¹ This study was initiated in 1993 to develop a basis for detecting climate change and for assessing aquatic carbon cycling in the Great Plains. After de-emphasis of detection studies by DOE, the implications of the work for estimating impacts of climate change on higher aquatic trophic levels allowed continuation of the project as important and necessary preliminary work to a follow-on modeling study.

agreement between the calendar-shifted climate for a test site (Gothenberg, Nebraska) and the nearest grid point computation of the equilibrium climate with 2XCO_2 radiative forcing² from the Canadian Climate Centre's GCM. Such provides comparable climate change scenarios to GCM-based scenarios that also preserve realistic intraannual serial correlations.

In the second year of a three-year study, Bogardi and colleagues at the University of Nebraska-Lincoln and the University of Arizona are developing and testing a stochastic technique for downscaling climate model-simulated atmospheric circulation patterns to derive local hydrologic quantities for impact analysis. They are relating simulated with observed circulation patterns; observed circulation patterns are then related to local surface climatological conditions. Impact analysis is performed by relating changes in surface climate from greenhouse warming to the Palmer Drought Severity Index to estimate drought frequency and intensity. *Important results to date show clear differences in average heights of pressure fields between 1xCO_2 (historic and modeled) and 2XCO_2 (modeled only) circulation patterns in Nebraska. Precipitation in the 2XCO_2 case was increased relative to 1XCO_2 but the variability was increased too, meaning fewer high-rainfall events.*

Two studies pertaining to climate modeling but less directly related to the specific research thrusts of the GPRC were supported. In the second year of a three-year project, Han and Welch at the South Dakota School of the Mines are investigating the relationships between cloud cover characteristics and ecosystem types. Also, the relationship between cloud droplet radii and the Net Difference Vegetation Index (NDVI) is studied across the Great Plains. Such information will help establish the possible interactions of climate change, cloud cover and ecosystem response on a large scale. *Important results to date include the findings that: (a) NDVI is directly related to cloud radii meaning that clouds form with larger droplet sizes over vegetated surfaces than nonvegetated surfaces; and (b) the relationship between aerosols, cloud droplet radii and albedo is not yet detectable for most regions globally.*

In the second year of a two-year study, Chen and Tribbia at Iowa State University and the National Center for Atmospheric Research (NCAR) respectively are studying the effects of Pacific sea-surface temperatures (SST) on interannual and interdecadal variability of winter atmospheric circulation using upper air observational data and post-WWII time series of circulation patterns in the NCAR general circulation model (CCM). *An important result to date is the finding that the global relative angular momentum (RAM) is a strong indicator of interannual variation of atmospheric circulation and also coincides with the Southern Oscillation Index with embedded SSTs. Inclusion of such components in the NCAR CCM enhances climate variability under the 2XCO_2 scenario.*

Modeling Impacts of Climate Change. Modeling approaches are being used in a number of studies to synthesize results of process studies and to estimate the regional scale consequences (impacts and adaptations) of climate change on some aspect of the natural resource base of the Great Plains. Although all of the studies with a regional modeling component are mentioned in this section, some of the studies focus primarily on Thrust 2 and are only identified here for further discussion under Thrust 2.

The Mearns and colleagues project described above is providing crop model estimates of the effects of high-resolution scenarios of climate change on productivity. In the second year of a three-year project, Brandle and colleagues at the University of Nebraska-Lincoln and Iowa State University are examining the influence of shelterbelts on micro- and meso-scale climate in the Great Plains. The practical importance of such work is the insight it provides into the ability of artificial and natural riparian shelterbelts to protect crops and habitat under conditions of climate change. Mechanistic modeling combined with direct field observations of microclimate in a fully replicated experimental shelterbelt system is used better to understand shelterbelt influences on crop microclimate. One of the mechanistic crop growth models used

² The term " 1XCO_2 " refers to a GCM representation of the equilibrium climate with greenhouse gas radiative forcing at current ambient levels. The term " 2XCO_2 " refers to a GCM representation of the equilibrium climate with CO_2 concentrations increased to a level that serves as a proxy for a doubling of all greenhouse gas (CO_2 , CH_4 , O_3 , CFC, etc.) concentrations above preindustrial levels.

in the Mearns and colleagues project is used here to examine the influence of shelterbelt-modified microclimate on crop productivity under assumptions of climate change. A modified forest gap model is being used to estimate the change in habitat in riparian forest systems as a first step in tracing the effects of climate change on species diversity in such systems. An economic input-output model is being modified to estimate the economic costs/benefits of shelterbelts with climate change based on crop modeling results. *Important results to date include the preliminary model finding that shelterbelts reduce regional evaporation rates by reducing near-surface turbulence. Also, crop productivity in shelter is not nearly as negatively affected by climate warming and drying as productivity in open field conditions. A forest dynamics model called "Seedscape" has been developed to predict species composition in Great Plains riparian forests; validation of the model and development of an animal response component have begun. Several scenarios have been tested to estimate the economic value of shelterbelts under the current Great Plains climate—optimally sized shelterbelts were found to provide net positive economic benefits, despite lost cropland to trees.*

Using the same crop growth model as Brandle and colleagues, Dyke and colleagues at Texas A & M University, Battelle-Pacific Northwest Laboratories and the University of Nebraska are in the first year of a three-year study examining the feasibility of substituting biomass fuel crops in place of existing crops in the Great Plains. In addition to estimating the agronomic and economic feasibility of biomass production under climate change, the crop model is coupled with a runoff model to provide comparisons of effects of existing cropping systems versus biomass production systems on regional runoff. *An important early result is that biomass (switchgrass) reduces erosion and runoff, but does not fare as well under a replay of the 1930s climate as traditional crops of the region, no account taken of elevated CO₂ or adaptation.*

In the first year of a three-year project, Neilson and colleagues at Oregon State University and Colorado State University are linking a watershed model (MAPSS) with a landscape-scale ecosystem process model (CENTURY) in order to understand regional changes in energy and water fluxes resulting from climate change in a mixed grassland-shrub-tree landscape in the Great Plains. The prototype modeling scheme is being developed with data from Wind Cave National Park in western South Dakota. *An important result to date is the successful validation of the MAPSS model with data from southwestern Idaho. The preparation of environmental data sets for Wind Cave National Park is nearly complete.*

The CENTURY ecosystem model is being used in two other projects summarized under Thrust 2 in order to determine soil organic matter (SOM) dynamics between different vegetation classes (see Tieszen and colleagues below) and among different land management strategies (see Elliott and colleagues below).

In the first year of a three-year project, Malanson and colleagues at the University of Iowa are examining basic properties regulating the scaling of the results of spatially explicit ecological models to surrounding landscapes in the Great Plains. Emphasis is given to the interactions of climatic gradients (temperature and moisture), seed dispersal and model grid cell size in determining species composition with a dynamic forest simulation model tailored to mid-continent locations. *An important result to date is that modeled species diversity across a large region is low in the absence of a climate gradient and increases dramatically with the introduction of only a slight gradient and is little affected by a still stronger climate gradient.*

Thrust 2: Measuring and Modeling Net Carbon Exchange

The measurement and modeling of processes of net carbon exchange in key Great Plains ecosystems is the second research thrust of the GPRC. Four projects are funded under this thrust, two of which are field-based process studies, the third is an integrated process and modeling study and the fourth is purely a modeling assessment.

Process Studies. In the second year of a three-year project, Verma and colleagues at the University of Nebraska-Lincoln, Colorado State University and the National Center for Atmospheric Research are examining surface fluxes of carbon dioxide and methane in mid-latitude prairie wetlands. Concurrent micrometeorological (eddy correlation) and chamber flux measurements are being made to relate fluxes with their underlying biophysical controls on a Nebraska Sand Hills wetland (near Valentine, NE).

Important results to date include partitioning of typical diel courses of clear day surface energy balance components into net radiation, heat storage in the water-sediment layer, sensible heat flux, and water vapor flux. Micrometeorological measurements found the wetland beginning the growing season as a source of CO₂ and changing rapidly to a sink until senescence when exchange rates approached zero. They also found that methane flux increased during the course of the growing season before declining to near zero with senescence. Significant diurnal differences in methane flux were found, with fluxes being significantly higher and more variable during the daylight hours than during the nighttime hours. Nighttime fluxes appear to correlate strongly with changes in sediment/water temperature. Chamber measurements of CO₂ flux confirm the patterns seen in the micrometeorological measurements, plus they suggest the fluxes may be related to canopy foliage area and water column temperatures.

In the first year of a three-year project, Ham and Knapp at Kansas State University are examining how changes in environmental and biological forcing and land management (grazing, burning) may regulate fluxes of carbon, water and energy from a tallgrass prairie (Konza Long Term Ecological Research site). A suite of micrometeorological measurement techniques initially will be used before settling on the technique that seems best suited to conditions. *An important result to date is the establishment of measurement sites and the assemblage of instruments to begin measurements over the summer of 1995.*

Modeling Studies. In the second year of a three-year project, Tieszen and colleagues at Augustana College, Iowa State University, University of Kansas, Colorado State University, EROS Data Center and the National Center for Atmospheric Research are examining carbon isotopic fractionation signatures of C₃ and C₄ plants in grassland ecosystems to determine whether or not such ecosystems are currently in a steady state with climate. Information generated from the isotopic fractionation analysis will be integrated with the CENTURY ecosystem model to examine carbon fluxes from various soil organic matter fractions under different land management schemes. Additionally, AVHRR-based vegetation indices are used to classify C₃ and C₄ vegetative cover classes to make regional assessments of net carbon exchanges based on the isotopic and modeling analyses. *Important results to date include the finding that, when examined independently, STATSGO and isotope data show that similar environmental variables (e.g., climate, soil texture) determine the proportional contribution to primary production, thus providing validation of the isotopic methodology. Moreover, from isotopic fractionation analysis it was found that the grassland soils studied here are not in a steady state with the atmosphere in terms of contribution to primary production, mainly because of anthropogenic influences. Yet, the unexpectedly high contribution of C₃ species to production cannot be totally explained by anthropogenic influences.*

In the second year of a three-year study that complements the work of Tieszen and colleagues, Elliott and colleagues at Colorado State University are examining the interactive effects of climate, elevated CO₂ levels and land management on soil organic matter (SOM) dynamics in the central U.S. wheat and maize production regions using the CENTURY ecosystem model. Analyses are structured to permit analysis of effects of existing cropping practices (tillage, crop rotation) on SOM dynamics, the effects of climate change on such, and the determination of the management practices under climate change and elevated CO₂ levels that optimize SOM accumulation. *An important result to date is the conclusion that changes in land management practices combined with higher CO₂ concentrations have a greater influence on SOM accumulation than changes in climate.*

Other Projects

Two projects with the goal of detecting and attributing climate change resulting from anthropogenic radiative forcing were completed this year. Though, work in this area is no longer emphasized by NIGEC and will not be supported further by the GPRC, important understanding was gained in these initial efforts. Gosnold and Todhunter at the University of North Dakota have studied transient perturbations in the geothermal gradient in connection with surface temperature observations along a north-south transect of observing points with the goal of detecting changes in the gradient that may signal greenhouse warming. *An important result to date is that borehole temperature profiles across the transect correlate strongly with latitude as indicated by climate model predictions of greenhouse warming.*

Lillesand and colleagues at the University of Wisconsin-Madison examined the timing and extent of mid-

latitude lake ice break-up as an indicator of climate change using remotely sensed imagery with a numerical thermodynamic lake ice model. *An important result to date stemming from sensitivity analysis of the model is that the ice-off date is more sensitive to air temperature than the ice-on date and that either is more sensitive to temperature warming than cooling.*

SUMMARY AND RECOMMENDATIONS OF FY94 GPRC PIs WORKSHOP

The GPRC hosted its first annual workshop of funded PIs September 29-30, 1994 in Lincoln. The main objective of the workshop was to facilitate collaboration among PIs leading to exchanges of data and information among projects as a first step toward integrating broad areas of research. The workshop was divided into two parts. The first part consisted of short plenary presentations of each of the funded projects. The second part consisted of breakout discussions focusing on four major research topics under the umbrella of the GPRC's research program: (1) biogeochemical cycling (Shashi Verma, chair; Jay Ham, rapporteur); (2) development of climate scenarios for impact analysis (Linda Mearns, chair; Michael Palecki, rapporteur); (3) managed and unmanaged ecosystem impacts (Ted Elliott, chair; David Guertin, rapporteur); and (4) scaling of data and model simulations (George Malanson, chair; Rollin Hotchkiss, rapporteur).

Each of the breakout groups was asked to focus on one or more of the following tasks: (1) identification of major strengths and gaps in the GPRC research program; (2) identification of specific potential interactions between one or more projects/topical areas; and (3) recommendation of specific new research topics to incorporate into the GPRC research program. A summary of discussion of each of the four breakout topics follows (Appendices I-A, I-B, and I-C contain rapporteurs' records of discussion for each of the groups, exclusive of the scaling group). It should be noted that while the scaling group discussions are summarized below, there is no record of discussion for the scaling group since most such issues are pervasive of the other three topical groups and thus were inserted into the other three group reports to avoid redundancy.

Biogeochemical Cycling Group. The common interest of the group was the conduct of field experiments to examine how key biogeochemical processes may interact with climate change in the Great Plains with the goal of understanding biophysical regulators of the biology, hydrology and trace gas dynamics of principal ecosystems. Among the strengths of the GPRC program in this regard are: (1) the integration of climate modelers with process-level scientists; (2) the conduct of net carbon exchange work at different scales using different measurement and modeling methodologies; and (3) the synergy the GPRC funding provides to ongoing work supported by other funding agencies, particularly on recognized research facilities (e.g., LTER sites).

Among the gaps in the GPRC program with respect to biogeochemical cycling are: (1) an imbalance of funded research that favors modeling efforts over measurement and experimentation; (2) the lack of a dynamic land use/land cover classification for the Great Plains for scaling *in situ* process studies; and (3) poor linkage between hydrologic models and carbon cycle/ecosystem models. The group recommended that high priority be assigned to the filling of those gaps in future GPRC grant competitions.

Several potential interactions among PIs conducting biogeochemical cycling work within the Great Plains region were identified. Examples include: (1) the application of stable carbon isotope analysis (see Tieszen and colleagues, this report) to grasslands (see Ham and Knapp, this report) and wetlands (see Verma and colleagues, this report); (2) comparison of trace gas flux measurement techniques (Ham and Knapp, Verma and colleagues, this report); and (3) application of carbon cycle/ecosystem models (see Neilson and colleagues, Elliott and colleagues, Tieszen and colleagues, this report) to soil core analyses (Blair and colleagues, this report).

Climate Scenarios Group. The development of a set of credible scenarios of climate change for application to impact analyses is essential to integrating individual impact studies. The group gave primacy to the need to assemble such a set of scenarios utilizing the work underway in three GPRC projects: (1) the down scaling of atmospheric circulation patterns to surface climate series through statistical associations (Bogardi and colleagues, this report); (2) the "nesting" of regional climate models

within general circulation models (Mearns and colleagues, this report); and (3) the shifting of the annual seasonal cycle, termed "calendar shifting," to create a new climate series. A strong recommendation of the group was for the GPRC to facilitate coordination of outputs from those three projects to create a package of usable alternative climate change scenarios to conduct impact model intercomparisons.

The group identified a major research priority concerning the development and use of climate change scenarios for impact analysis: the need to conduct sensitivity analysis with impact models to determine a range of possible outcomes in order to account for the high level of uncertainty and possibility of surprise inherent in the climate change scenarios.

Managed and Unmanaged Ecosystem Impacts Group. Recognizing the broad charter of the impacts group, a framework was developed to organize a discussion of research gaps and needs under the ecosystem impact headings of: (1) productivity; (2) carbon storage; (3) water quality and availability; and (4) biodiversity. The framework identified major research approaches, key underlying processes, driving variables and necessary data bases for each of the impact headings.

Major research gaps identified under productivity included the need: (1) for adaptation of forest production models to represent riparian forest systems in the Great Plains; (2) for development and manipulation of models of various aspects of animal (livestock and wildlife) response to change in climate and habitat; (3) to conduct process studies of plant growth response to climate change with higher atmospheric CO₂; and (4) to examine pest response to climate change and possible implications for plant productivity. The group stressed the need for development of appropriate data bases for virtually all aspects of impact analysis.

Major research gaps identified under carbon storage included the need: (1) to develop stronger linkage between remotely sensed imagery and process studies of biophysical controls of net carbon exchange processes (*Director's note: this obviously overlaps with the biogeochemical cycling group recommendations and is addressed below*); (2) to develop mass balance equations for below ground carbon storage as affected by climate change and higher atmospheric CO₂ (*Director's note: this recommendation is addressed below*); and (3) to understand effects of land management processes on terrestrial carbon storage and the role of methanogenesis in carbon storage. A data base of land use and land management is critical (*Director's note: this need echoes recommendations of the biogeochemical cycling group and is addressed below*).

Major research gaps identified under water quality and availability include the need: (1) to adapt models of reservoir water quality to assess climate change impacts; (2) to develop groundwater models that are responsive to climate change conditions; and (3) to incorporate wetland driving variables as examples of small-area, high-influence ecosystems. Major research gaps identified under biodiversity include the need: (1) to develop and refine "metapopulation" models; (2) to conduct studies of genetic diversity; (3) to examine effects of climate change on landscape structure and habitat as a basis for studying the overall response of biodiversity to climate change. Again, data bases for examining the impacts of climate change on biodiversity are not available, except in special cases (e.g., the Breeding Bird Survey).

Scaling Group. The scaling group identified a small set of research needs that warrant future attention of the GPRC, especially as the first round of GPRC research projects nears completion and results must be integrated/synthesized, including: (1) the tracking of residual values from process and modeling studies such as, for example, following the route taken by water left by crop growth models in undefined soil layers toward stream runoff or the coupling of evapotranspiration from plants with regional climate models; and (2) properly weighting the role of strong but geographically small signals (for example, whether explicitly to represent a wetland in a landscape model or to average the wetland into the landscape).

Actions Prompted by the Workshop

Several recommendations made by the groups were studied and prioritized for potential action by the GPRC Director in concert with the GPRC Scientific Advisory Committee. As a result of high priority recommendations, efforts have begun:

* To coordinate the assemblage of climate change scenarios produced with three different techniques (stochastic downscaling of Bogardi and colleagues, nested regional modeling of Mearns and colleagues, and calendar shifting of Palecki and colleagues) into a package to be made available to other NIGEC investigators in need of climate change driving variables. Dr. Mearns is leading the development of the package.

* To insert a land use/land cover change component to the impacts thrust of the GPRC in order to develop a dynamic land use/cover classification that is responsive to climate and other environmental and human forcing.

* To fund with FY95 money new studies of: (a) the effects of elevated CO₂ and climate change on above and below ground partitioning of biomass for native prairie species (Charles Rice, Kansas State University); (b) the effects of climate change on pest (grasshopper) physiology and population characteristics (Anthony Joern, University of Nebraska-Lincoln); and (c) the effects of climate change on the surface hydrology of the Missouri River system with explicit linkage to water resources.

A recent survey of GPRC PIs (with limited response) found some tangible instances where the workshop discussions either prompted the development of research teams to assemble appropriate proposals or the exchanges of data and information between funded research teams, including: (1) the development of the Missouri River project mentioned above linking surface hydrology with water resources and economics; (2) the transmission of root biomass data from the soil study of Blair and colleagues to Tieszen and colleagues for use in modeling soil organic matter changes under climate change; (3) coordination of graduate student training between groups (for example, Tieszen's referral of students to Rundquist).

Research Integration with ARM-CART: Eco-ARM

Under the auspices of the GPRC and Battelle/Pacific Northwest Laboratories (PNL), discussions began in FY93 to plan the development of an ecological research effort to complement the research activities and utilize the facilities of the DOE's Atmospheric Radiation Measurement-Central Area Research Testbed (ARM-CART) program in eastern Oklahoma-Kansas. The GPRC and PNL co-hosted a workshop in March, 1994 in Lincoln to bring agency representatives and researchers together to assess the desirability and feasibility of such an effort. The workshop produced a broad outline for a proposed research program known informally as "Eco-ARM." Possible research topics of Eco-ARM include: (1) dynamics and net ecosystem exchange of greenhouse gases in grasslands and agro-ecosystem, (2) linkages of soil moisture, temperature and greenhouse gas fluxes in grasslands and agro-ecosystems, (3) impacts of management practices on greenhouse gas fluxes, (4) response of plants to CO₂ - enrichment under the wide range of soil and climatic conditions within the ARM-domain, (5) influence of vegetative cover on watershed dynamics and water quality, (6) effects of biomass plantations on surface radiation balances, energy balances and carbon budget, and (7) comparative studies of biomass productive capacity and management methods under varied climatic and soil conditions of the ARM-CART site.

GPRC and Battelle follow-on efforts to the workshop over the remainder of FY94 INCLUDED: (1) the development of a prospectus of research on climate and land use change interactions with surface fluxes of carbon dioxide and water vapor across the ARM-CART ecotones; (2) a site visit by a team of researchers to the ARM-CART region to assess potential flux measurement sites and to outline a research strategy; (3) the development of multiple proposals for funding of the research components of such a strategy; and (4) continued negotiation with ARM program managers to secure support for instrumentation.

Significant progress has been made toward development of a research project on climate and land use change interactions with trace gas fluxes. Research led by Dr. Easterling to examine land use change-ecosystem interactions in the ARM-CART region will be funded by the National Science Foundation. Dr. Shashi Verma of the University of Nebraska-Lincoln, a GPRC investigator, has developed a proposal to measure and model carbon dioxide and water vapor fluxes and their biophysical controls on two different land covers (tall grass prairie and wheat) in the ARM-CART region. Elements of Dr. Verma's proposal will be submitted to the GPRC.

Also, the GPRC is actively soliciting proposals that focus on some aspect of the GPRC's research thrusts within the ARM-CART region.

FUTURE DIRECTIONS FOR THE GPRC

The GPRC will continue efforts to develop a set of interconnected studies leading to an accumulative assessment of the impacts of climate change on the Great Plains and the quantification of the region's net carbon exchanges to and from the atmosphere. In addition to new efforts discussed in the previous section, the GPRC will stress the development of team research that mechanistically links process-level information on impacts and net carbon exchange with ecosystem-level models. Strong linkage will also be sought between ecosystem models and socioeconomic analysis.

Work that mutually complements the research goals of the GPRC and the ARM-CART program in Kansas-Oklahoma, especially that which focuses geographically on the ARM-CART region and utilizes data and/or instrumentation suites there, will receive high priority for funding. Research relevant to the GPRC that focuses on other dedicated research sites in the Great Plains (LTER sites, protected natural areas, agricultural experiment station testplots) is also encouraged.

APPENDIX I-A

BIOGEOCHEMICAL CYCLING GROUP REPORT

Jay Ham, Rapporteur

Great Plains NIGEC Workshop, Lincoln, Nebraska

September 29-30, 1994

Members and Participants

Shashi Verma (chair), Jay Ham (rapporteur), John Blair, Vern Cole, Joon Kim, Don Rundquist, Larry Tieszen, Frank Ullman, Dave Gosselin, Kyle Hoagland

Introduction

The biogeochemical cycling group was primarily composed of scientists that were conducting field experiments to examine how key biogeochemical processes may interact with climate change in the Great Plains region. The goal of most of the group was to obtain a better understanding of the biophysical processes that influence the biology, hydrology, and trace gas dynamics of principal ecosystems and land use types. The objectives of the breakout group session were: (1) identify strengths and gaps within the regional program; (2) examine possible interactions within the biogeochemical cycling group; (3) develop a flowchart of feedback and interactions between the different research groups; and (4) make a list of questions and research needs to present to the other breakout groups.

Strengths and Gaps Within the NIGEC Program**Strengths**

- ✓ Diverse Scientific Expertise. The regional program employs scientists with wide range of scientific skills and backgrounds. It is rare to see an integrated project that has global climate modelers interacting with process-level scientists working with microscopic/local mechanisms. This is exciting because an understanding of climate-terrain feedback can only be achieved when the dynamics of the entire terrestrial-atmosphere continuum are considered.
- ✓ Research at Multiple Scales. The NIGEC program is funding projects that operate at multiple spatial and temporal scales. This effort should allow experimental findings at micro and local scales to be extrapolated to regional levels. Additionally, regional climate change scenarios from large scale GCM models will allow local scale scientists to formulate better hypotheses and conduct more realistic field experiments.
- ✓ Valued Added Projects. Much of the research conducted as part of NIGEC will benefit other research efforts not directly linked to NIGEC (e.g., NSF LTER sites).
- ✓ Diverse Funding Sources. Many of the NIGEC investigators appear to have obtained funding from other sources to supplement their regional projects. Thus, the NIGEC program acts as a catalyst to stimulate extramural funding.

Gaps in the Regional Program

- ✓ Lack of Balance Between Measurement and Modeling. The group was concerned that the regional program contained too much modeling and not enough measurements. While the biogeochemical group clearly saw the value of modeling, they did believe that modeling must be done with at least "one foot in the field". That is, measurements must be used to develop better process-level submodels and to verify the performance of regional models by comparing measured and modeled results.
- ✓ Land-use Classification. Many researchers believed that land use and changes in land use need to be quantified for the Great Plains. Scaling procedures can not be employed without this information.

- ✓ Standardization of Field-Study Data Collection. Experimenters working on different ecosystems and land use types should work with modelers to develop a list of variables that are measured at all locations.
- ✓ Control and Patterns of Large Scale (synoptic) Weather Patterns / Air Movement.
- ✓ Improved Linkage Between Hydrologic Models and Ecosystem models.
- ✓ Seek Linkage Between NIGEC and Other Great Plains Projects (e.g., LTER sites)

Possible Interactions Within the Biogeochemical Processes Group

- ✓ Application of stable isotope analysis to grasslands and wetlands (Tieszen, Verma, Ham)
- ✓ Application of soil biogeochemical models (i.e, Century) to soil core experiment and wetlands study (Blair, Rundquist, Tieszen, Verma, Neilson and Ojima)
- ✓ Aerial extent of emergent vegetation by satellite remote sensing (Rundquist, Verma).
- ✓ Comparison of flux monitoring techniques (Ham, Verma).
- ✓ Interaction between soil microbial processes and the surface energy balance (Ham, Blair, Rice)

Diagram of Interaction Within the Regional NIGEC Program

The group developed a flowchart depicting the exchange of information between the different research groups within NIGEC (see attached figure). The rationale for the chart was as follows: (1) the process-level studies will provide basic information/submodels to the crop/range/ecosystem models; (2) the ecosystem models will couple the process-level information with regional climate drivers to simulate the effect of climate on biophysical-mediated productivity and trace gas dynamics (any many other parameters); (3) the results from the ecosystem models will be used to determine the impact of climate on the regional land-use changes, C Budget, hydrology, etc.; (4) regional responses will be used to estimate the socioeconomic impact of climate; (5) Climate change will be influenced by the dynamics of the region as well as influence regional climate (thus completing the loop); and (5) mitigation practices can be explored to reduce the impact of the region on climate change.

Questions for the Other Breakout Groups

The biogeochemical cycling group did not formulate a set of specific questions for the other research groups. However, the group did want to know how the information that they were collecting was going to be incorporated into regional scale research. It was clear that the process level researchers will need to find collaborators within the regional modeling groups to scale their findings to regional levels.

Proposed Interactive Flowchart
Great Plains Regional Research Program
NIGEC Regional Center, Lincoln, NE

Proposed by Biogeochemical Processes Group
NIGEC Regional Meeting, Lincoln, NE 9/29/94

CLIMATE CHANGE SCENARIOS GROUP REPORT
Michael A. Palecki, Rapporteur
Great Plains NIGEC Workshop, September 29-30, 1994

September 29

Participants: Linda Mearns (Chair), Michael Palecki (Rapporteur), Istvan Bogardi, Ken Dewey, Lucien Duckstein, Istvan Matyasovszky, Clinton Rowe, Dan Leathers, Gene Tackle, Reka Molnar, Wolfgang Diemhofer, Roland Reiter

Three main topics occupied the Climate Change Scenarios group:

- 1) What is the best way to facilitate collaboration among the three major research groups that are developing climate change scenarios for the Great Plains (First Order Collaboration)?
- 2) Are there outstanding issues and/or research gaps in the provision of climate change scenarios that should be addressed (General Issues)?
- 3) How will the information contained in group scenarios be made available to other Great Plains Center research groups (Second Order Collaboration)?

Topic 1: First Order Collaboration

The major collaborative effort of the group will be an intercomparison of climate change scenarios for the Great Plains of the United States. Each scenario generation method will be driven by the same GCM run. In order to facilitate this activity, a detailed discussion of each of the three scenario-generation methods represented in the group was required. This dialogue was structured so as to allow for an exploration of the techniques being utilized, the strengths and weaknesses of each method, and the climate variables output for each scenario.

The group led by Bogardi is using a down scaling technique (DS) that statistically relates fields of large scale atmospheric circulation to surface climate states. First, observed 500 mb atmospheric circulation patterns are reduced to principal components and then clustered into individual classes. This is done separately for each of the four seasons. The temporal properties of each circulation type are identified, focusing on their persistence and transitional probabilities. The probabilities of any given day having a certain 500-mb circulation pattern can then be modelled as a Markov process. In addition, probability distributions for climate variables (e.g., precipitation occurrence, precipitation amount, temperature, etc.) exist for each type of circulation, so one can synthesize time series of surface climate variables. To create a scenario, the 500 mb geopotential height and circulation pattern probability changes from a control GCM run to a doubled-CO₂ GCM run are added to the observed heights and circulation probabilities, allowing the statistical generation of scenario time series of any length.

A new and seemingly simple approach to climate scenario generation called calendar shifting (CS) is offered by the group led by Palecki. This approach uses large scale regional temperature differences between doubled-CO₂ and control GCM runs; in this case, the change in the annual cycle in the Great Plains is calculated from model output. These monthly temperature differences are then referenced to the observed annual cycle, and the time period of the year with the equivalent temperature is determined. Observations from the newly selected calendar dates are then used to represent the model scenario month in question. In mid-summer, observations from a limited subset of warm years are used to provide scenario information beyond the range of the normal annual cycle at a location. The final product is a set of re-ordered but genuine climate observations that are dynamically consistent.

A nested modelling (NM) approach to future climate scenario production is being employed by the group led by Mearns. A large scale global domain model run of a doubled-CO₂ climate is used to provide the boundary conditions for a mesoscale climate model. The mesoscale model is then operated over the

same time interval as the driving global GCM model nm. The enhanced resolution of the mesoscale climate model allows for the production of a high resolution climate change scenario based on first physical principles. Observed daily variances are then incorporated with the modelled climate changes to complete the scenario.

All of these approaches to climate change scenario production have strengths and weaknesses. The DS method relies on one of the most robust fields modelled by GCMS: the large scale mid-tropospheric geopotential height patterns. The stochastic nature of the resulting scenario product allows for the assessment of changes in the probabilities of extreme climate anomalies with long recurrence intervals. In addition, observed spatial relationships between locations are maintained within the generated scenario. Finally, the DS method has wide-ranging applicability, as the same approach can be applied to many different variables.

Some of the same features of the DS method that are important advantages in scenario production can also be considered to be disadvantages. The assumption of a fixed relationship between circulation patterns and surface climate variables through a period of climate change can never be verified. Further, the control run GCM circulation classes are somewhat different from those observed. Even larger problems exist with the method during summer months, when midtropospheric flow and precipitation are often decoupled.

Climate modelling approaches have one compelling advantage above all semi-empirical methods: the resulting scenario is based on the available theoretical knowledge about the response of the climate system to the physical forcing of increased atmospheric CO₂ levels. Feedbacks between atmospheric and surface processes during climate change are fully represented. The NM strategy has the additional benefits of high spatial resolution, complete physical consistency between variable fields over space and time, availability of all climate variables of interest, and total spatial and temporal coverage for a region.

Unfortunately, the NM approach is computer intensive, and, therefore, resource restrictions limit the length of model runs. More importantly, many processes are not well described by physical laws at the aggregation scale of model grid cells, forcing a reliance on parameterizations that may not be valid under perturbed forcings. In addition, errors in the global-scale GCM climate can be propagated into the nested model through boundary layer conditions.

The CS technique has the advantage of simplicity. By relying on the direct time translation of daily observations, all scenario variables are dynamically consistent with each other, and natural modes of variability are fully represented. The technique may be applied to many different surface variables simultaneously, once the shift calendar has been identified.

The major assumption made when operating the CS method is that a seasonal shift forcing is analogous to an increased CO₂ forcing. In addition, it is concluded that the relationships between all the different surface climate variables is maintained through a period of changing climate. Finally, the CS approach does not allow for possible changes in the association between mean climate variable states and their variances.

Topic 2: General Issues

After clarifying the methods of scenario production, including their advantages and disadvantages, the group commenced a more philosophical discussion regarding the merits of scenarios for impact assessments. Is there a reason for using complicated methods to generate improved scenarios? Has the nature of scenarios changed in some fundamental manner? In response to these questions, a statement was made and agreed to that scenarios have become more complex, but that we are no closer to confirming their validity than we were in the past. The possibility of unexpected outcomes still remains large. It became clear that everyone is assuming that global warming will take place, whether this conclusion is based on physical principles or GCM runs. This may leave us in the dangerous state of not having tested our impacts models for the effects of an unanticipated outcome, such as a temporary cooling. Perhaps some more effort must be applied to understanding the uncertainties of any one climate

change scenario being validated. It is recommended that all impacts modelers, even if they normally examine the response of their models to realistic climate change scenarios, should also run their impacts models through carefully controlled sensitivity analyses covering a wide range of possible outcomes.

Topic 3: Second Order Collaboration

The availability of variables from each scenario was discussed in the context of the needs of impact assessors. The DS method can produce probability changes for almost any surface climate variable with sufficient observations to establish a relationship with circulation. All desirable climate variables are available from the NM approach; selected variables must not exceed mass storage capacities, and must be requested before the model run. All climate variables that have sufficiently long time series to characterize a mean seasonal cycle, except those directly involving radiation, can be derived from the CS method once the time shift dates have been determined.

A brief set of variables - maximum temperature, minimum temperature, and precipitation - has been chosen for special consideration in scenario intercomparisons and for standard output products to be archived for second order collaborators. Variability statistics may also be included in this archives. The spatial domain of the DS scenario will be limited to selected stations, while the NM and CS scenarios will cover the region of the Great Plains. Each scenario will be produced using the same doubled-CO₂ model run as its starting point in order to facilitate intercomparison. Assuming the global GCM model run is available by March 1995, the DS and CS groups will have their scenarios completed by late summer 1995, while the NM runs will not be completed until late 1995.

The conditions for use of the scenarios by the impacts community led to the discussion of an important philosophical problem: do we let impacts people do what they want, or do we try to limit their usage to appropriate applications? The decision was made to provide written guidance regarding the assumptions of each scenario producing method, their shortcomings, and suggested limitations regarding their appropriate use. In fact, the scenario producers will be available to act in an advisory capacity to other impact assessors, perhaps through the organization of a workshop for this purpose. One of the primary recommendations that should go forward to the impact assessors is to test their own models through sensitivity analyses and simulations of historically warm periods like the 1980s. Further discussions with a wider community of impact assessors is needed to examine our recommendations and comment on them.

September 30

Participants: Linda Mearns (Chair), Michael Palecki (Rapporteur), Istvan Bogardi, Ron Neilson, Kyle Hoagland, Jim Brandle, John Blair, Jay Ham, Bill Smith, Dave Gosselin, Tony Joern, and John Antle.

The main goal of this session was the exchange of information between climate change scenario producers and climate change impact assessors. The dialogue was organized around a sequential presentation of the data input needs of various impact assessment projects, followed by a brief discussion of the logistics of scenario availability.

Studies of large-scale changes in vegetation require monthly temperature, precipitation, humidity, and wind speed data. Even with the best resolution scenarios, additional software packages must still be used to interpolate data onto finer grids over complex terrain. One approach to the integration of scenario data is to take the observations of climate variables interpolated over study regions, and then multiply them by the ratio of doubled-CO₂ to control scenario output variables. Differencing (doubled-CO₂ minus control) is utilized in altering temperatures only.

Many climate change impact assessments must be performed on truly microscale levels of detail, especially when concerning agricultural applications. Pests such as grasshoppers are temperature dependent, as well as forage dependent. Susceptibility to pest outbreaks is often keyed to climate conditions over very small areas, such as sections of counties. When looking at agricultural conditions around shelter belts, the local climate changes are of paramount importance; small shifts in wind statistics

can create differential impacts. The assumption must be made that the microclimatological spatial behavior during observed extreme warm events must be similar to those in a doubled-CO₂ future, as there is no way to independently determine these patterns. Studies of climate change impacts on small water bodies and wetlands also have similar scaling concerns, and demand climate change variables that are usually not available, such as sunshine and evaporation.

The major theme that emerged from this discussion was scale. Even with the advent of scenario production methods which output data at grid scales or station separation distances of 50 km, there is always going to be a need for further down scaling of the information to local and even microscales. This is an especially difficult problem when dealing with process-level models calibrated at individual sites. It was concluded that process model developers and impact assessors must be the ones to develop their own specific ways of using available scenario information at microscales.

A discussion of the type of climate variables that are included in scenarios, and the assumptions under which scenarios are developed, reviewed for the new participants much of the content of the previous session. The types of variables of interest to impacts assessors goes well beyond the typical temperature and precipitation variables, to include relative humidity, surface hydrology, wind speed and direction, net radiation, sunshine hours, and photosynthetically active radiation. In addition, some of these variables must be characterized at more frequent than daily time intervals. The DS scenario approach can provide time series of any of these variables, as long as a sufficient time series of observations exist to characterize the variables at a location. This is also true of the CS technique, although it is not recommended for use in determining radiation variables. Finally, the NM method, although capable of producing any variable field of interest, is in practice limited to a set of major fields due to mass storage requirements: maximum temperature, minimum temperature, relative humidity, incoming solar radiation, wind speed, and clouds. Any variables not saved during the model run are lost. All three methods will produce variance statistics for the selected scenario variables.

The three types of scenarios will be available for use by impact assessors during NIGEC Fiscal Year 1995. Results for the DS and CS methodologies will be available for several different GCM guidance runs, although only a subset of the Great Plains region will be available from the DS group. Documentation of techniques and assumptions will be archived along with the scenarios, and each group will provide guidance to these products. If sufficient interest arises, a workshop on the use of climate scenarios may be organized. Overall, the exchange of information and ideas proved to be quite useful for both the climate change scenario users and the impact assessors.

MANAGED AND UNMANAGED ECOSYSTEM EFFECTS GROUP REPORT

David S. Guertin, Rapporteur
Great Plains NIGEC Workshop, Lincoln, Nebraska
September 29-30, 1994

Participants

Ted Elliott (Chair), David Guertin (Rapporteur), Jim Brandle, Geoff Henebry, Kyle Hoagland, Tony Joern, Ron Neilson, Chuck Rice

INTRODUCTION

In the Great Plains, few ecosystems could accurately be called completely unmanaged, but some systems are managed more intensely than others. Wetlands, for example, are not entirely unmanaged, but are still less intensely managed than crop lands. Our discussion in this group therefore considered effects on ecosystems under varying intensities of management.

By using a common approach to various topics in this discussion, we may link disparate projects together through related processes, and identify topics and research areas that have received little attention to date. We derived a framework containing five components (Fig. 1). Relevant issues or impacts of climate change are areas of study with both scientific importance and policy relevance. For each issue we identified important research approaches, and processes, driving variables, and data bases that serve as inputs to these research approaches. These areas are discussed below and are summarized in Table 1. Within this framework, we identified important areas of overlap in research topics, as well as gaps in research that should be addressed.

ISSUES

We discuss four important impacts of climate change. This is not an exhaustive list, but rather the topics that received the most attention within the breakout group. The discussion below refers to the items listed in Table 1, especially those topics that were specifically identified as research gaps. Note that Table 1 does not specifically list climate, land use and management, and economics and policy as driving variables. These three variables are driving variables for all impacts of climate change, and therefore are not listed separately in the table; they also are important gaps in our current knowledge. While data are available for past and current climate, prediction of future climate is very uncertain. Effects of land use and management and economics and policy on each of the four impacts discussed are also largely unknown.

1. Productivity

Prediction of potential effects of climate change on productivity is an important research topic for a wide range of ecosystems, including intensively managed systems such as crop lands, where development of cropping systems in response to climate change is an important goal. Effects on productivity are also important to understand in less managed systems such as grasslands (importance of grazing patterns), aquatic systems (phytoplankton populations as essential components of food webs), and wetlands. In some parts of the Great Plains region, forested systems are present, and production models for Great Plains forests is an important gap in our knowledge. Most studies of productivity do not include the role of animals, and this also is a research gap.

Reservoirs and ground water are important inputs to productivity for which our current information is deficient. The roles of both plant growth and pests (including insect, plant, and microbial pests) in productivity are also important gaps in knowledge. Table 1 lists three data bases for studies of productivity, but overall there is substantial room for improvement in data bases both for developing and for testing models.

2. Carbon Storage

Models and mass balance equations are two types of approaches to carbon storage. Models are fairly well developed, with the exception of remote sensing models. The below-ground components of carbon storage, are however, very little known.

Three processes affecting carbon storage deserve more attention. The effects of management practices is little known, as are some aspects of herbivory. The role of methanogenesis has been gaining increasing attention. A data base of land use and management would be useful, but none is available currently. DEM data on elevation are available for large scales, but not small scales.

3. Water Quality and Availability

Water resources are critical for both intensively managed and less managed systems. Hydrologic models are well-developed, but models of reservoir water quality and ground water models are not. Most inputs to these models are fairly well-studied, with the notable exception of the role of wetlands as a driving variable in the models.

4. Biodiversity

Effects of climate change on biodiversity are best studied using a population-or community-level approach. Metapopulation models are particularly well-suited to heterogeneous landscapes; this approach is still not fully developed, but its use is growing. Definitions of biodiversity vary; species diversity may be a gauge of the health of ecological communities, or particular species may act as indicators of community response to climate change. Studies of genetic diversity have been underrepresented but have been getting increasing attention. The effect of climate change on habitat and landscape structure, and thus indirectly on biodiversity, is a significant research gap.

Dispersal, migration, bioenergetics, and habitat use are processes that affect population approaches to biodiversity. These are all species-dependent processes, and although they are known for a small number of species, they are unknown in many more. Data bases relevant to biodiversity are scarce. Some data bases, such as the Breeding Bird Survey, are available, but overall the availability of data is a large gap in knowledge.

CONCLUSIONS

Our discussion could not identify all research topics that are relevant to climate change and ecosystems; nevertheless, it did bring to light several important research gaps. In addition to those listed above, the development of a land-use model would be an important aide to research in the Great Plains. This corresponds with land-use being an essential driving variable for all research approaches in this region, and underscores the importance of human economic systems as influences on ecological systems. Consideration of spatial and temporal scaling is also essential in most research approaches.

Finally, we recommend three improvements to the logical structure of the Great Plains Regional research program. First, the importance of land use as a driving variable should be made more prominent. Second, there should be more explicit incorporation of scaling. Third, the program is more usefully viewed in two separate but related frameworks: 1) the organization of the Great Plains regional project, and the research programs contained within it; and 2) the organization of scientific concepts and knowledge (e.g. Fig. 1).

Table 1: Components of each of the four main issues discussed. Bold text denotes items that were identified as research gaps. Climate, land use/management, and economics/policy were identified as driving variables for all four issues, and are not included in the table.

Components	Issues			
	Productivity	Carbon Storage	Water Quality/Availability	Biodiversity
APPROACHES				
	<ul style="list-style-type: none"> • Production models: <ol style="list-style-type: none"> 1. crops 2. grassland 3. forest 4. aquatic/wetland • Experimental manipulation • Remote sensing • Animals 	<ul style="list-style-type: none"> • Models: <ol style="list-style-type: none"> 1. plants 2. soils 3. remote sensing 4. ecosystem • Mass balance calculations <ol style="list-style-type: none"> 1. Below-ground components 	<ul style="list-style-type: none"> • Hydrologic models • Reservoir water quality models • Ground water models 	<ul style="list-style-type: none"> • Level of modeling: <ol style="list-style-type: none"> 1. population 2. metapopulation 3. community • Type of diversity <ol style="list-style-type: none"> 1. genetic 2. species 3. functional groups • Habitat approach
PROCESSES				
	<ul style="list-style-type: none"> • Plant growth • Nutrient cycling • Water balance • Water quality degradation • Reservoirs • Ground water 	<ul style="list-style-type: none"> • Water balance • Decomposition • Production (net) • SOM formation/loss • Management • Fire • Herbivory • Methanogenesis 	<ul style="list-style-type: none"> • Runoff • Infiltration • Percolation • Evapotranspiration • Productivity 	<ul style="list-style-type: none"> • Dispersal • Migration • Bioenergetics • Habitat use

continued on next page

Table 1: continued from previous page

Components	Issues			
	Productivity	Carbon Storage	Water Quality/Availability	Biodiversity
DRIVING VARIABLES	<ul style="list-style-type: none"> • Nutrients • Pests 	<ul style="list-style-type: none"> • Water table • Topography 	<ul style="list-style-type: none"> • Runoff • Productivity • Vegetation • Wetlands • Consumption 	<ul style="list-style-type: none"> • Biophysical constraints • Habitat/landscape
DATA BASES	<ul style="list-style-type: none"> • Agr. census data • SCS data • Remote sensing data • overall 	<ul style="list-style-type: none"> • Land use/mgmt. • Soil (esp. C) • Productivity • DEM (elevation) 	<ul style="list-style-type: none"> • State water plans • USGS hydrol. regions • snow pack 	<ul style="list-style-type: none"> • Breeding bird survey • overall

Figure 1: Framework used to view impacts of climate change on ecosystems. Appropriate research approaches are used to address each issue. Each approach has its own set of inputs, which take the form of processes, driving variables, and data bases.

Appendix I-D

**GREAT PLAINS REGIONAL CENTER FOR GLOBAL ENVIRONMENTAL CHANGE
FUNDED PROPOSALS/PROJECTS
1994-95**

PRINCIPAL INVESTIGATOR	PROJECT TITLE	AMOUNT	INSTITUTION(s)
VERMA, Shashi B. Valentine, David W.	An Integrated Investigation of Methane and Carbon Dioxide Fluxes in Mid-Latitude Prairie Wetlands: Micrometeorological Measurements, Process-Level Studies and Modeling	280,000	UNL CSU
MEARNS, L. Giorgi, F. Easterling, W. Weiss, A.	Development of a Nested Regional Model for the Conterminous United States and Formation of High Resolution Climate Change Scenarios with an Application to Crop Climate Models	118,000	NCAR UNL
TIESZEN, Larry L.	Assessment of Climate and Management Induced Directional Changes in Great Plains Vegetation with NDVI and Stable Carbon Isotopes	80,000	Augustana
BLAIR, John M. Todd, Timothy C. Rice, Charles W. Knapp, Alan K.	Effects of Altered Soil Moisture and Temperature on Soil Communities, Primary Producers, and Ecological Processes in Grassland Ecosystems	82,500	KSU
BRANDLE, James R. Easterling, William E. Takle, Eugene S.	Assessment of Climate Change on a Mixed Agricultural and Forest Landscape on the North American Great Plains	102,000	UNL ISU
ELLIOTT, Edward T. Cole, C. Vernon	Regional projections of C Dynamics with Global Change in the Central U.S.	100,000	CSU MSU
HOAGLAND, Kyle D. Ernst, Stephen G.	The Detection of Climate Change Using Living and Extinct Diatom Floras	55,000	UNL
BOGARDI, Istvan Matyasovszky, Istvan Duckstein, Lucien	Space-Time Local Hydrology Influenced by Changing Climatology: Disaggregation, Prediction and Comparison	120,000	UNL U of AZ
HAN, Qingyuan Welch, Ronald M.	The Effect of Ecosystems on Cloud Microphysics and Aerosol Distribution	63,000	SDSMT
DYKE, Paul T. Rosenberg, Norman J. Easterling, William E.	The Comparative Economics and Environmental Impact of Biomass for Energy Production under new Digester Technologies and Increased CO ₂ Levels	70,000	TX A&M Battelle UNL
NEILSON, Ronald P. Ojima, Dennis Lenihan, James Daly, Christopher	Potential Global Warming Impacts on Vegetation Distribution, Productivity, and Hydrology at Landscape to Regional Scales in the Great Plains Region	40,000	OSU CSU

**GREAT PLAINS REGIONAL CENTER FOR GLOBAL ENVIRONMENTAL CHANGE
FUNDED PROPOSALS/PROJECTS
1994-95**

PRINCIPAL INVESTIGATOR	PROJECT TITLE	AMOUNT	INSTITUTION(s)
RUNDQUIST, Donald C. Gosselin, David C.	Natural Responses of Shallow Lakes and Wetlands for Detecting Climatic/Environmental Change	75,000	UNL
CHEN, Tsing-Chang Tribbia, Joseph J.	Observational and Numerical Study for Interannual and Interdecadal Variabilities of the Atmospheric Circulation	35,000	ISU NCAR
PALECKI, Michael A. Dewey, Kenneth Leathers, Daniel J. Robinson, David A.	The Detection of Climate Change Using Long Term Daily Climate Records Over Grassland Regions of the Northern Hemisphere	86,000	UNL U of DE Rutgers
GOSNOLD, William D. Todhunter, Paul	Climate Change in the Midcontinent of North America	40,000	U of ND
LILLESAND, Thomas M. Magnuson, John J.	Satellite Observation of Lake Ice as a Robust Indicator of Regional Climate Change	40,000	UW-M
HAM, Jay M.	Carbon, Water, and Energy Fluxes From a Tallgrass Prairie: A Long-term Investigation of Biological, Environmental, and Land Use Factors	30,000	KSU
MALANSON, George P.	Local and Regional Scaling With a Spatially Explicit Ecological Model	20,000	U of IA

Great Plains Regional Center Integrated Research Program

Great Plains Regional Center for Global Environmental Change

Effects of Altered Soil Moisture and Temperature on Soil Communities, Primary Producers and Ecological Processes in Grassland Ecosystems

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Objectives: We are investigating the potential consequences of climate change for grassland biological systems, focusing on functional effects at the individual, community and ecosystem levels. For the tallgrass prairie ecosystems at the eastern edge of the Central Plains region, patterns and amounts of precipitation, along with fire frequency and grazing, are key factors controlling ecosystem structure and function. The importance of climate, particularly precipitation, as a forcing function makes these ecosystems especially vulnerable to the changes in precipitation and temperature predicted by current global climate change models, although not enough is known to predict the magnitude of these changes or how they will affect ecosystem function over longer time scales. Our specific objectives are (1) to determine the responses of prairie grasses, soil organisms and key soil and plant processes to different soil moisture and temperature regimes and (2) to identify the potential consequences of these responses for ecosystem function in light of the predictions of global climate change models.

Products: Our research will provide new insights into the effects of altered soil moisture regimes on ecological processes in grasslands. This information is important for correct interpretation of the consequences of predicted shifts in the regional climate. Results of this research will be directly relevant to the Department of Energy's Global Change Research Program priority question regarding the response of terrestrial organisms and ecosystems to potential changes in climatic conditions (precipitation and temperature), the regulation and controls of these responses, and how these responses are integrated across organizational levels to produce adjustments in terrestrial ecosystems to climate change. Specific question we address are:

1. How will changing soil moisture levels and temperatures, a predicted consequence of global climate change models, affect plant productivity, soil communities and soil processes in tallgrass prairie ecosystems of the Central Plains region?

2. What are the likely consequences of changes in primary productivity, soil communities and soil processes for grassland ecosystem function (i.e., organic matter storage and turnover, nutrient retention and availability)?

Approach: We use naturally occurring gradients of soil moisture and/or temperature, at two very different scales, as experimental "treatments" to address the controls which moisture and temperature impose on ecological processes in grasslands. At a regional scale we have selected two sites (a mesic tallgrass prairie and a more arid mixed-grass prairie) with different climatic influences due to an east-west precipitation gradient. The more mesic tallgrass site is located at Konza Prairie Research Natural Area (KPRNA - 39°05N, 96°35W), and the more xeric mixed-grass site is at the Fort Hayes Agricultural Experiment Station (FHAES - 38°75N, 99°20W). A major component of our research involves reciprocal transplants of large intact soil cores and associated plants between these sites to address the effects of altered soil moisture availability and temperature on selected response variables. Seventy intact soil cores (25 cm diameter x 70 cm deep, encased in open-ended PVC cylinders) were extracted from both the KPRNA and FHAES sites using hydraulic soil coring equipment. At both sites cores were taken from areas dominated by *Andropogon gerardii* (big bluestem) to minimize variability among cores. Half the cores were placed back into holes at the site from which they were taken, and half were transplanted into holes at the other site, so that the soil surface of in situ cores was flush with the surrounding soil. The end result was a grid of 35 paired "tallgrass cores" and "mixed-grass cores" arranged in a randomized block design at each of the two sites. Data from "native" (non-transplanted) cores at each site allows us to compare soil communities, properties and processes in grassland ecosystems developed under different climatic regimes, while data from transplanted cores provides insights into how plants and soil communities, properties and processes respond to altered soil moisture and temperature. The use of "non-transplanted" cores also controls for

the effects of the coring operation and encasement of the cores in PVC for the duration of the experiment. A representative subset of cores ($n=5$ of each core type at each site) has been instrumented to allow continuous remote monitoring of soil moisture, using Time Domain Reflectometry (TDR), and soil temperature. Sufficient cores were transplanted to allow for (1) intensive destructive sampling during the three-year funding period and (2) less intensive monitoring of longer-term (i.e., ten years) changes. A set of 10 cores from each site is destructively sampled twice a year (spring and autumn), and analyzed for total above- and below-ground plant biomass C and N, soil invertebrate numbers and composition, microbial biomass and activity, total soil N and C, and available soil N.

At a more local scale (KPRNA only) we are utilizing field sites with different average soil moisture availability, resulting naturally from topographic position, to examine the long-term responses of tallgrass ecosystems to different soil moisture and temperature conditions. We are using difference in water availability between upland and lowland sites to address the effects of chronic water stress on plant reproductive effort, biomass and NPP. In addition to these naturally occurring moisture gradients, we have expanded our local studies to include sampling along a topographic sequence to which supple-

mental irrigation water is added to reduce growing season water deficits. Both the regional reciprocal transplant experiment and the control and irrigated transects studies are relevant to understanding the consequences of climate change in the Central Plains region.

Results to Date: Research in the second year is progressing on schedule. Establishment of sites and placement of intact soil cores for the reciprocal core transplant experiment was completed in 1993, and sets of cores for periodic sampling and analyses were collected in May 1994, November 1994, and May 1995. These cores were processed and sampled for a suite of variables including: above- and below-ground biomass, plant nutrient content, extractable soil N, potentially mineralizable soil C and N pools, soil microbial biomass C and N, and soil invertebrate abundance and community structure. Many of these analyses are ongoing, but results to date have been useful for characterizing existing differences in plant and soil properties at our two field sites, and have already suggested some responses to changes in climate associated with the transplanted cores. For

Fig. 1. Biomass and depth distribution of grass rhizome and root biomass in cores collected in November 1994, one year after the start of the reciprocal transplant experiment (see text for explanation). Percentages next to horizontal bars represent the percentage of total live grass root mass found in each of the four depth increments sampled.

Fig. 2. Potentially mineralizable soil N (Fig. 1A) and soil C (Fig. 1B) in 0-5 cm deep soils from intact cores collected in May 1994. Circles are soil cores originally from Hays and squares are soil cores originally from Konza. Solid symbols represent soil cores which had been left at their site of origin, while open symbols represent cores reciprocally transplanted in November 1993 (see text for explanation). Note the significant decline in cumulative N and C released from Hays cores transplanted to the Konza site.

example, there were initial differences in both total below-ground biomass and depth distributions of grass roots at the Konza and Hays sites (Fig. 1). The chronically drier conditions at Hays were associated with both lower total rhizome and root biomass, and differences in the depth distribution of root biomass, compared to Konza cores. We also found some marked differences in the potentially mineralizable C and N pools in soils from the Konza and Hays sites (Fig. 2). Soils from Hays exhibited faster rates of soil C and N mineralization, relative to soils from the Konza site, when incubated under standard laboratory conditions, suggesting greater accumulations of mineralizable C and N in the more xeric site. One of the most interesting findings to date has been an apparent rapid decline in potentially mineralizable soil N in the transplanted Hays cores. Upper horizon (0-5 cm) soil collected in May of 1994 from FHAES cores which were relocated to the Konza site exhibited a much lower mineralization potential than soil from FHAES cores which remained at the Hays site (Fig. 2A). A similar pattern was observed for potentially mineralizable C (Fig. 2B). Preliminary results from incubation of cores collected in November of 1994 indicate the same directional changes in mineralizable C and N of transplanted cores. These incubations, when completed, will allow to calculate the initial size of the potentially mineralizable soil N and C pools (N_0 and C_0), as well as determine the response of these pools to changes in climate over time. We also have been able to document differences in the abundance and distribution of soil nematode at the Konza and Hays sites (Fig. 3). Although we have not detected significant changes in total nematode abundance with the core transplants, we have found some shifts in the relative abundance of certain species. For example, a *Helicotylenchus* sp. which had a low abundance at Hays has become a dominant species in Hays cores transplanted to Konza. This is a different species than is normally found in Konza. Analysis of soil microarthropods samples are ongoing.

Measurements of plant ecophysiological responses also were initiated at both sites in spring of 1994, and being continued in 1995. Physiological responses of *A. gerardii* native to each site are being compared with those of *A. gerardii* transplanted from the reciprocal site. Measurements included midday leaf xylem pressure potentials, and leaf-level net

photosynthesis, measured with a LICOR portable gas analyzer. Results to date are presented in Fig. 4. Midday water potentials indicated greater early and late season water stress at the Ft. Hays site, relative to cores at the Konza site. The effects of these periods of water stress on leaf level photosynthetic rates are apparent. These ecophysiological responses were translated into reduced aboveground productivity at the Hays site. Additional non-destructive indices of plant density and phenology also are being done to document differences in stand characteristics and plant phenology at the two sites.

In 1994 we expanded our measurements of plant productivity and soil N availability across topographic gradients at the KPRNA field site to include irrigated and non-irrigated transects. These measurements are being continued in 1994, with the addition of measurements of soil CO_2 flux. A related project in 1994 examined topographic patterns of soil N availability and above ground net primary productivity (ANPP). Results of that study demonstrated greater ANPP at wetter lowland sites, with the differences between upland and lowland sites being enhanced by burning. Surprisingly, topographic patterns of soil net N mineralization were the opposite of patterns of ANPP, and net N mineralization was greater at the drier, upland sites. The effects of soil moisture deficits on these patterns will be addressed as data from the irrigation transects become available.

Fig. 3. Densities of total soil nematodes by depth in cores collected in November 1994, one year after the start of the reciprocal core transplant experiment. There was a significant core origin depth interaction, indicating significant differences, by depth, between cores from Hays and Konza.

Manuscripts in preparation and submitted:

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Turner, C.L., J.M. Blair, R.J. Scharz and J.C. Neel. Soil N availability and plant response in tallgrass prairie: Effects of fire, topography and supplemental N. Submitted to Ecology.

Presentations:

Blair, J.M. 1994. Decomposition of above- and below-ground grass litter in tallgrass prairie ecosystems. 14th North American Prairie Conference, Manhattan, Kansas, July 1994.

O'Lear, H.A., T.R. Seastedt, J.M. Briggs, J.M. Blair and R.A. Ramundo. 1994. Decomposition of wood in soils of burned and unburned tallgrass prairie. 14th North American Prairie Conference, Manhattan, Kansas, July, 1994.

Blair, J. M., H. Su, J. C. Shaw and A. K. Knapp. 1994. Effects of topography and fire on soil processes and plant productivity in tallgrass prairie. Ecological Society of America meeting, Knoxville, TN, August 1994.

Knapp, A.K., J.M. Briggs and J.M. Blair. 1995. Long term ecological research at the Konza Prairie Research Natural Area: Lessons in sustainability from a native Great Plains ecosystem. Planning for a Sustainable Future: Great Plains Symposium, Lincoln, NE, May, 1995.

Fig. 4. Seasonal (1994) ecophysiological responses of big bluestem (*Andropogon gerardii*) in the reciprocal core transplant experiment (see text for explanation). Top panel: mid-day leaf water potentials. Lower panel: Leaf-level net photosynthesis.

Student Participation (FY 94 only):

In FY 1994 two graduate students and a total of nine undergraduate student research assistants were involved in research and training activities supported by this project.

Name	University	Degree Sought	% Time on Project	NIGEC Funds Received
Sherry Ahlgrim	Kansas State U.	B.S.	10%	\$ 954
Sherry Antholtz	Kansas State U.	B.S.	<5%	\$ 206
Deane Coulson	Kansas State U.	B.S.	50%	\$ 2,150
Mitchell Emig	Kansas State U.	B.S.	25%	\$ 1,162
Brian Haverkamp	Kansas State U.	B.S.	25%	\$ 1,455
Cathy Hitchcock	Ft. Hays State U.	B.S.	25%	\$ 3,953
Angela Lambley	Kansas State U.	B.S.	25%	\$ 578
Krista Mobley	Kansas State U.	B.S.	50%	\$ 3,010
Jeffrey Neel	Kansas State U.	B.S.	50%	\$ 5,428
Heather O'Lear	Kansas State U.	M.S.	100%	\$ 8,216
Antonio Omay	Kansas State U.	Ph.D.	75%	\$ 7,564
				<u>\$34,676</u>

Space-Time Local Hydrology Influenced By Changing Climatology: Disaggregation, Prediction and Comparison

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Objectives: A stochastic downscaling technique will be developed and applied for estimating local/regional hydrological quantities reflecting global climate change. Specific objectives include: (1) Relate the arrival rate of atmospheric circulation patterns of a given type to the probability of space-time hydrological variables. (2) Provide a tool for using existing synoptic outputs of GCM for prediction of space-time hydrological variables at a regional or watershed level. (3) Compare and evaluate the climate change impact on hydrological variables over several regions of the United States and Europe.

Products:

1. A validated methodology will be available to estimate local/regional hydrological impacts of global climate change. The methodology has been and will be published in refereed journals or conference proceedings (Bardossy et al. 1995; Bardossy et al. 1993; Bartholy and Duckstein, 1994; Bogardi et al. 1994b; Bogardi et al. 1994c; Bogardi et al. 1994a; Bogardi et al. 1994d; Duckstein et al. 1994a; Galambosi et al., 1995; Matyasovszky et al. 1993a; Matyasovszky et al., 1993b; Matyasovszky et al. 1994a; Matyasovszky et al. 1994b; Matyasovszky et al. 1994c; Ozelkan et al. 1994a, 1994b; Pesti et al. 1994; Weidinger et al. 1994).

2. Quantitative information on the expected hydrological impacts of climate change will be available for the regions considered.

3. Computer codes will be available upon request to facilitate the application of the methodology to other regions. Although these codes have been used extensively by us and by our cooperative partners, their successful application will require a modest familiarity with the methodology.

Approach:

Circulation Pattern (Cp) Data. Three types of daily Cp data are used.

1. Historical data are represented by the National Meteorological Center (NMC) grid point analyses of the height of 500 hPa pressure fields available from the National Center for Atmospheric Research (NCAR). The analysis is based on daily values (12⁰⁰ UT) at 40 points on a diamond grid covering the sector 25 -60 N, 80 -125 W for the period January 1948-June 1989, which covers the central USA.

2. A 10-year long data series for the same pressure level has been obtained from the output of MPI (Max Planck Institute for Meteorology, Hamburg, Germany) and CCC (Canadian Climate Centre) GCMs corresponding to the 1xCO₂ scenario.

3. An analogous series has been obtained from the 2xCO₂ scenario.

Compiling Circulation Pattern (Cp) Types.

We used principal component analysis (PCA) coupled with k-means because a conjunctive use of these techniques usually provides the most separable system of clusters with the most concentrated clusters (Bartholy, 1992). We also used a fuzzy rule-based approach (Bardossy, et al. 1995; Ozelkan, et al. 1994b).

Relating Local Climate to Cp Types.

To reproduce the space-time statistical structure of local climatic factors, a suitable model should be chosen. Autoregressive processes represent a well-developed and commonly used tool to model time series. They have been developed principally for Gaussian processes, but climatic

factors do not usually follow a Gaussian distribution. Therefore, it is desirable to construct a transformation establishing a relationship between the distribution of a local climatic factor and a normal distribution. Let the vector $\mathbf{Z}(t) = (Z(t, u_1), Z(t, u_2), \dots, Z(t, u_k))$ represent a daily climatic variable at locations $u_1, u_2, \dots, u_k$ and time t and let $\mathbf{W}(t)$ be a K -dimensional normal random vector at time t . We suppose for simplicity that each component of the vector $\mathbf{W}(t)$ has unit variance. The time dependency of $\mathbf{W}(t)$ is described using first order autoregressive (AR(1)) processes. The transformation of the random vector $\mathbf{Z}(t)$ into the normal vector $\mathbf{W}(t)$ depends on the climatic variable under consideration as shown for rainfall in Matyasovszky et al. (1993b) and for temperature in Matyasovszky et al. (1994b).

Special Consideration for the $2\times\text{CO}_2$ Data.

We have shown that the Cp characteristics within a given Cp type may change which means that knowledge of the Cp type alone may not be enough and that additional parameters have to be introduced to describe Cps under climate change. We used the geopotential height of a pressure level as an indicator of the atmospheric pressure and temperature. The anticipated warming due to the increasing concentration of CO_2 gas is accompanied with the expansion of atmosphere so that pressure levels are located at larger heights. The concept to correct for systematic over- or underestimation of the geopotential heights is as follows. The annual cycle, i.e., changes in the expectation of geopotential height within the year is considered as an analogy of the difference between geopotential heights corresponding to the present and $2\times\text{CO}_2$ climates. The relationship between parameters of the daily climatic variables and spatial average height is described using historical data and is then used to estimate the effect of climate change on these local variables. To this end, we investigate how the probability distribution of local climatic variables (conditioned on Cp types) at a given location depends on the actual height of the 500 hPa pressure field.

Probability distributions are estimated corresponding to the $1\times\text{CO}_2$ and $2\times\text{CO}_2$ monthly mean heights of the 500 hPa pressure field, and the probability distribution calculated from the whole historical data set is adjusted according to the difference between the two above mentioned distributions (CO_2 case). Specific forms of this

adjustment are described for precipitation in Matyasovszky et al (1993b) and for temperature in Matyasovszky et al. (1994b).

Results to Date:

1. A general framework for studying hydrologic uncertainties related to climate change has been developed in Duckstein and Parent (1993), Duckstein (1994), Duckstein et al. (1994a) and Waterstone et al. (1993)
2. Nine stations for analyzing precipitation data and four for temperature data have been selected in eastern Nebraska where two seasons are distinguished for precipitation and each month is examined separately for temperature. Ten stations for analyzing both precipitation and temperature data over four seasons have been selected for the Arizona case study, because of the variety of climatic zones in the state. Other data, such as wind and evapotranspiration are being gathered. Stations in New Mexico are also being selected as a function of length and reliability of records.
3. Daily atmospheric circulation patterns (Cp) have been classified objectively or automatically using principal component analysis (PCA) with the k-means approach. For the Great Plains, this procedure yields nine Cp Types in both the winter and summer seasons (Bogardi et al. 1993). Cp's have been classified subjectively on the basis of the types defined in Bradley et al. 1982 for the central Arizona case for the three seasons (summer, autumn, winter) in which watershed hydrology can be simplified; namely, without mix of rain and snowmelt (Duckstein et al. 1993). Fuzzy rule-based and neural-net based classification of the 500 hPa Cps has been constructed for Western Europe and then the two Western basins under consideration, that is, central Arizona and the Upper Rio Grande Valley (Bardossy et al. 1995; Bartholy and Duckstein, 1994; Galambosi et al. 1995).
4. Precipitation over nine Nebraska sites and ten Arizona sites have been conditioned on the time series of Cp types and then simulated using a split sample technique with historical data. On the basis of the model described in Matyasovszky et al. 1993a, most encouraging results have been obtained on this dependence of space-time precipitation upon time series of Cp types.

5. A ten-year time series of daily Cps obtained from the output of two GCMs (Canadian Climate Center and Hamburg Model) have been analyzed in the cases of $1xCO_2$ and $2xCO_2$ using the same techniques as for historical data (Bogardi et al. 1994a; Galambosi et al. 1995). No significant difference in either typology (by CPA) or Markov properties (transition probabilities from one type to another one) could be found for either season (summer or winter).

6. In order to utilize the above GCM results, the average height of the 500 hPa Cps has then been taken as a third characteristic of Cps under climate change, leading to a clear differentiation between the $1xCO_2$ case (historical or GCM produced) and the $2xCO_2$ case (GCM produced) in Nebraska (Matyasovszky et al. 1993a).

7. Precipitation over the Nebraska sites appears to exhibit different but site specific behavior in the $2xCO_2$ versus $1xCO_2$ cases; overall, there is only a slight increase of mean precipitation but the variability of precipitation increases substantially; namely, fewer events with greater rainfall depths are found to occur (Matyasovszky et al. 1993b). Results in Arizona and New Mexico are very station dependent.

8. Floods in Central Arizona have been conditioned on daily Cps defined subjectively occurring over an optimum time window before the flood event, found to be three days (Duckstein et al. 1993). Extreme precipitation is also being investigated (Ozelkan et al. 1994).

9. The Cp output of two different GCMs has been used to downscale temperature and rainfall in eastern Nebraska, Arizona and New Mexico. Both GCMs resulted in similar tendencies but somehow different local responses to climate change (Matyasovszky et al. 1994a; Duckstein et al. 1994b).

10. A methodology for predicting various drought indices (PDSI and Bhalme-Mooley Index) under climate change has been developed and applied to eastern Nebraska (Bogardi et al. 1994a, 1994b) and New Mexico (Pesti et al. 1994).

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Climate Change in the Midcontinent of North America

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Objectives: This research critically tests use of the geothermal gradient as a tool for studying climate change on temporal scales of decades to centuries and applies the method in a comparison of the calculated ground-surface-temperature history with the air temperature record along a 2000 km north-south transect in the midcontinent of North America. The theoretical basis for this project is that temporal changes in the average surface temperature cause transient perturbations in the geothermal gradient that may be analyzed to determine the ground-surface-temperature history. Climatic

zones along a north-south transect in the midcontinent of North America vary systematically with latitude so that any climate change, either warming or cooling, should be observable as a shift of the zones along the transect. In theory, the amplitude of any change also should vary systematically with latitude. Specifically, climate simulations of global warming due to a doubling of CO₂ predict that the amplitude of warming would be greater near the poles and lesser near the equator (Hansen et al., 1988; Mitchell et al., 1990; Bretherton et al., 1990). Thus, if the predicted warming is

occurring, this midcontinent transect offers a favorable study area for detecting the signal. However, direct correlation between the ground-surface-temperature history, as calculated from existing geothermal gradient data, and the historical air temperature record has not been tested. Our objectives are to test and evaluate the relationship between the ground temperature record and the air temperature record and to apply the results in an analysis of climate change in the midcontinent of North America.

Products: (1) An understanding of the relationship between the ground surface temperature and the air temperature over a complete annual cycle. (2) A comparison of the climate changes determined by analysis of air temperatures and borehole temperatures. (3) An analysis of climate change in the midcontinent of North America during the past several centuries. (4) A detailed profile of the climate histories over the instrumented period at our three climate station-borehole sites.

Approach: To investigate century-scale climate change, we are performing inversions on t-z profiles from 45 existing boreholes that were drilled and completed specifically for heat flow research in the Great Plains province between 1979 and 1990 (Gosnold, 1990). To investigate decadal sensitivity of the borehole data, we are remeasuring t-z profiles in all existing boreholes drilled between 1979 and 1984 and are comparing the results of inversions of the original and new t-z profiles. The computational method uses a least-squares inversion of the temperature-depth (t-z) profile to calculate a ground surface temperature (GST) history at the borehole site (Shen et al, 1995, 1992). The results of the inversions are essentially change from the long-term temperature mean; that is, the ground surface temperature that would be seen by the borehole in a steady-state condition where no climate change has occurred.

To examine air-ground coupling in conjunction with inversion of t-z profiles, we drilled three boreholes at carefully selected locations and installed automated weather stations and subsurface temperature monitoring instruments on the sites. Further investigation of air-ground coupling uses soil temperature and climate data available through a network of automated climate stations operated by the Regional Weather Information Center at the University of North Dakota (RWIC), the High Plains Climate Center

at the University of Nebraska - Lincoln (HPCC), and the Microclimate Research Station operated by North Dakota State University in Fargo. To test the geographic coverage of individual boreholes, we are evaluating the correspondence between our borehole climate stations and all climate stations within a 250 km radius of the borehole sites.

Results to Date: We have performed inversions on 24 existing borehole t-z profiles in addition to the three boreholes we drilled for this project. We tested the correlation with latitude for the calculated temperature increases for the 27 sites (Figure 1) and found that the 95 percent confidence limits on the correlation coefficient lie between 0.48 and 0.85. Our conclusion at this time is that the borehole data show a climate change that correlates with latitude as has been predicted by greenhouse gas warming scenarios.

We have remeasured t-z profiles in 4 holes in Nebraska, 9 holes in South Dakota, and 3 holes in North Dakota. The Nebraska holes were drilled and logged initially in 1980, and comparison of the 1995 and 1980 data revealed that the ground surface has warmed by 0.2 K in the past 15 years. The South Dakota sites were drilled and logged initially in 1990 and there was no significant difference between the inversions of the 1990 and 1995 logs. The 3 sites in North Dakota were drilled in 1983 and logged initially in 1984. All 3 showed ground warming of 0.4 K during the past 11 years.

We have drilled heat flow holes and installed automated climate stations at three sites that meet our strict criteria for borehole sites for paleoclimate studies. The localities in Texas, South Dakota and Manitoba are described in detail in our 1993 Progress Report. The criteria are: absence of microclimatic disturbances due to surface topography, no land use changes, shale bedrock, no potential for vertical ground water flow, and no terrain effect on the geothermal gradient. The stations record daily observations of: air temperature, relative humidity, incident and reflected radiation, snow depth (South Dakota and Manitoba sites only), wind speed and direction, and soil temperatures at 0, 1, 10, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10000 cm depths.

Thermal conductivities measured on core samples from the three sites are important with respect to the objectives of this project and with

respect to the interpretation of heat flow data from boreholes in shale in general. Measuring shale thermal conductivities has been problematical for several reasons. First, unless special handling is employed, the core samples will rapidly desiccate and begin to change thermal conductivity within minutes after they are removed from the core barrel. Second, shale samples are typically soft and tend to fall apart in a divided-bar thermal conductivity apparatus. Third, few core samples of shales have ever been available for measurement. Consequently, virtually all published heat flow values from boreholes in shale have been based on

estimated or inaccurately measured thermal conductivities.

Our Texas site provided a unique opportunity to address this general problem due to the close proximity of the Geothermal Laboratory at Southern Methodist University. At the SMU laboratory, we were able to measure thermal conductivity on the carefully preserved samples of the Eagleford Shale using three different techniques, i.e., a divided-bar, a QTM, and a half-space needle probe. The measured thermal conductivities in W/m/K are as follows:

Depth (m)	Needle Probe	Divided Bar	Qtm
31.0 - 32.6	0.67	—	1.05
57.0 - 58.5	0.72	0.68	0.81
79.9 - 81.4	0.72	0.76, 0.70	1.00
104.2 - 105.8	0.74	0.87	0.89

The agreement between the needle probe and divided bar results on the Eagleford Shale indicated that the needle probe, which is portable and battery powered, would be suitable for use in the field. Therefore, we used the half-space needle probe for Pierre Shale samples from the South Dakota and Manitoba sites. The mean thermal conductivity of 60 measurements spaced over 240 m at 40 m intervals on the Odonah member of the Pierre Shale in Manitoba is 1.2 ± 0.2 W/m/K. The mean for 60 measurements on the Pierre Shale at Wall, South Dakota is 1.9 ± 0.25 W/m/K at 50 m and 2.2 ± 0.25 W/m/K at 101 m. Samples at 200 m were too fragile to measure. Currently, we are conducting grain size and compositional analysis of the samples from all sites.

Our analysis of ground-air coupling has produced significant results through numerical modeling

and through analysis of soil and air temperature data from RWIC, HPCC and the NDSU Microclimate Research Station. Our computer models test ground-air coupling by using the historical air temperature data to drive the subsurface thermal regime. The results of the models, which are temperature-depth profiles that would obtain under various coupling conditions, were compared to measured temperature-depth profiles from Minot, North Dakota, Wall, South Dakota and Valentine, Nebraska. The modeling exercise provides three estimates of climate change: the first is the historical air temperature record, the second derives from numerical inversion of the model result and the third derives from numerical inversion of actual borehole data. The results of models assuming 1:1 ground air coupling are given in Table 1.

Table 1. Comparison of temperature changes observed at climate stations, borehole models assuming 1:1 ground-air coupling, and actual borehole data.

Location	Air Temp dT/100 y	Model Inversion dT	Data Inversion dT
North Dakota	1.4 (0.138)	0.72	1.75 (4)
South Dakota	0.4 (0.013)	0.47	1.43 (4)
Nebraska	0.4 (0.024)	0.28	0.60 (3)

The numbers in parentheses under the air temperature column are the values of r^2 for the linear least squares regression. The numbers in parentheses in the data inversion column give the number of borehole profiles used and the values are averages. The low correlation coefficients for changes in air temperature result from the high interannual variability of air temperatures and emphasize the statistical uncertainty in analyzing climate data. Since the ground filters the high frequency signals and retains only the long-term temperature changes, the second column, Model Inversion, represents a more accurate determination of change in air temperature over the past century. The correlation of temperature change with latitude appears distinct; however, three samples are insufficient to test this analytically. The most important result of this modelling exercise is that the actual borehole data record significantly larger temperature increases than are seen in either of the other two methods.

Following the above tests, we began analyzing soil and air temperature data available from the HPCC, RWIC and CDIAC FTP sites. The analyses suggested that the difference between the borehole data and the models was that the models did not account for seasonal snow cover or latent heat released during freezing of soil moisture. Subsequently, we developed models that include seasonal snow cover and latent heat but did not achieve better correspondence with the warming trends seen in the borehole data. The insulating effects of snow cover and the latent heat released by freezing soil moisture cause ground temperatures to be warmer than air temperatures such that the difference between the two correlates with mean temperature and, in the midcontinent, with latitude. However, this difference could not cause a secular warming trend in the GST unless its effect also increased with time. We doubt that such a trend could be largely controlled by snow cover since Spring snow cover has decreased for the past 20 years in the Northern Hemisphere (Groisman, Karl, and Knight (1994). This led us to suspect that soil moisture may be a key factor in determining ground surface temperatures. In fact, precipitation data from CDIAC (Groisman and Easterling, 1994 shows that annual precipitation has increased by more than 100 mm in the past 50 years in the Northcentral United States and Canada. At this time we tentatively conclude that a secular increase in precipitation in

northerly latitudes where the ground freezes for significant periods has caused a secular increase in ground surface temperatures. This causes borehole temperatures in those regions to record greater warming than has actually occurred. This is a significant result since only 15 of the 362 borehole sites in North America that have been analyzed for GST histories lie in regions that do not experience seasonal ground freezing.

Manuscripts in preparation and submitted:

The geothermal gradient and climate change, in preparation for submission to *Science*.

Presentations:

The geothermal gradient and climate change, International Workshop on Borehole Temperatures and Climate Change, Prague, Czech Republic, 1995.

Analysis of the geothermal gradient as a method of paleoclimate reconstruction, American Geophysical Union Fall Meeting, 1994.

Heat flow data from core holes at the Manson Impact Site, Geological Society of America Annual Meeting, 1994.

Interpretation of Temperature-depth Logs from Boreholes in Manitoba and Saskatchewan, GAC - MAC Annual Meeting, Waterloo, ONT, 1994.

Student participation: William Schmidt 100%, Paul Abell 100%, Tim Freije 25%, Steve Smith 25%.

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GST history vs. latitude

Assessment of Climate Change on a Mixed Agricultural Landscape on the North American Great Plains

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Introduction: The Great Plains is a grassland ecosystem that has undergone large-scale conversion to agriculture. Linear forest systems (shelterbelts and riparian corridors) are the dominant forest ecosystem of the region and play important roles in the overall landscape. We postulate that these systems have an influence on the local microclimate far beyond their size and contribute significant ecological and economic values to the Great Plains agroecosystem.

Objectives: The goal of this project is to examine the potential impacts of climate change on the roles trees play in Great Plains ecosystems. This report will deal with three objectives addressed during the past year: 1) to estimate the effect of linear forests on wind flow and the resulting microclimate as the basis for estimating how climate change may alter this effect, 2) to estimate the effects of potential climate change on biological diversity in riparian forests in the Great Plains, and 3) to estimate the economic impact of existing shelterbelts on regional (ND, SD, NE, KS) economies.

Products: The products defined here represent those expected at the conclusion of the study. Intermediate products are discussed in the approach section and are described as they relate to individual steps within the entire scope of the project.

1. An understanding of the influence of a regional system of linear forests on wind flow and the resulting microclimate of crop fields.
2. An assessment of the ability of shelter to moderate the potential impacts of a changing climate on crop production in

sheltered fields.

3. An individual-based model to predict tree species diversity in the Great Plains under conditions of climate change.
4. An avian species diversity model based on the habitat characteristics of linear forested strips found in the Great Plains.
5. An analysis of the economic impacts of linear forests found in the Great Plains under changing climate scenarios.

Approach and Results to Date:

Wind flow responses: A nonhydrostatic shelterbelt turbulent boundary-layer model was used to simulate the effects of various shelterbelt configurations and approach wind angles on horizontal and vertical profiles of wind speed.

Using the numerical model, we have examined the changes to the flow field in the lee of a shelterbelt when the wind is perpendicular to the belt. The model shows, and field studies confirm, that the location of maximum wind reduction moves toward the shelterbelt when the approach flow direction departs from normal, and that the wind speed in shelter may exceed the undisturbed wind speed in the region 3 to 15 H to the lee because of the channeling effect of the shelterbelt (see Figure 1).

The change in sheltering effect due to an oblique wind is partially a result of the increase of effective density due to the longer path through the belt for oblique flow. On the other hand, the shelter cannot reduce the wind component parallel to the shelter as efficiently as the component perpendicular to the belt. These two factors depend on incident angle and height.

Regional shelterbelt networks alter not only the atmospheric boundary-layer structure and surface drag force, but also the mesoscale regional radiation and energy partitions and the water balance. Comparative analysis in China has shown that regional mean wind speed was reduced by 20%, regional evaporation was reduced by 14%, and air temperature increased by 0.4°C in spring and decreased by 0.3°C in summer. Preliminary simulations of a regional network of shelterbelts with the ISU shelterbelt model showed that, although turbulence is increased within the shelter, near-surface turbulence intensity over the sheltered region is greatly diminished. It is this near-surface turbulence that affects the energy, mass, and water vapor transport, therefore the network causes a reduction in regional evaporation by reducing near-surface turbulence.

Biological diversity: Forest dynamics models are frequently used to predict the effects of climate or other environmental conditions on species composition and diversity of forests (see Figure 2). *SEEDSCAPE*, a forest dynamics model similar in structure to *JABOWA* and *FORET*, has been modified to represent Great Plains riparian forests by incorporating:

1. a spatially explicit landscape mosaic up to 1 km², instead of homogeneous forests;
2. plot-specific tree growth conditions based on local soil types within this landscape;
3. plot-specific initial vegetation types;
4. dispersal of seeds from seed-producing trees to plots throughout the landscape;
5. fluctuating water table in riparian zones (highest in spring, lowest in autumn);
6. increased light availability to plots at edges of forest corridors;
7. incorporation of commercially minor but ecologically important tree species of the Great Plains.

SEEDSCAPE is currently configured to model conditions found at the University of Nebraska Agricultural and Development Center (ARDC) near Mead, Nebraska where the model is being developed. Climate data are from a riparian site at ARDC. Climate change is currently modeled as a 3°C increase in temperature and a 30% decrease in precipitation. Regional climate change scenarios from Mearns et al. (this report) will eventually be used in *SEEDSCAPE*.

The construction of the model is complete.

SEEDSCAPE has undergone initial testing, and the model output is consistent with vegetation sampled in a riparian forest corridor at ARDC. Currently, modeled effects of climate change on vegetation are still preliminary until *SEEDSCAPE* is more thoroughly validated. Validation of the model simulation is to be completed by the end of summer 1995 after comparisons with historical vegetation records at ARDC and elsewhere in Nebraska.

Regional economics:

We are examining shelterbelts within the broader agricultural production system and attempting to integrate their numerous economic benefits using a systems approach. This entails assimilating market and non-market benefits such as increased productivity, erosion control, ecological enhancement, climate change buffering capacities, recreational opportunities, and aesthetic enhancement.

Efforts to this point have focused on measurement of crop productivity benefits in a four state region including: ND, SD, NE and KS. *ImPlan* (an input/output model developed by the USDA-Forest Service) has been utilized in determining the order of magnitude of the Great Plains regional economic benefit of existing shelterbelt systems.

Three different impact scenarios were modeled for seven major crops: corn, wheat, soybeans, sunflower, sorghum, oats and barley. Crop yield responses were based on previously published yield studies. Results are an estimate of the magnitude of the response of the economy to shelterbelt technology.

In the first scenario, a final gross benefit to the regional economy was measured. Shelterbelts were found to provide an additional \$253 million to gross regional product. Total industrial output and employee compensation benefits were positively impacted by \$337 and \$46 million respectively. Jobs provided by the benefits of shelter total 3952 and population is 6422 persons greater than would otherwise be the case.

The second scenario measures the opportunity cost of leaving land in shelter versus cropping those acres. Results show a cost to the regional economy of \$17 million in gross regional product, \$22 and \$3 million in total industrial output and employee compensation benefits, a net job loss

of 393 and a population which is smaller by 242.

The third scenario examines the final benefits of optimally sized shelterbelts (i.e., no wasted acreage on excess shelterbelt widths) which was simulated by increasing total production in the appropriate commodity sectors. In this scenario, the opportunity cost of production foregone on acres occupied by shelterbelts is less than was found in scenario two. An appropriately designed system of shelterbelts was found to increase gross regional product by \$53 million. Total industrial output and employee compensation benefits are \$69 and \$10 million higher. Jobs provided total 823 while the population is 1338 persons greater. Therefore it appears that the impact on the regional economy of a system of shelterbelts is dependent upon appropriate design.

Student participation: Mr. Mark Marsh is a Ph.D. student in Economics at UNL and is working on the economic assessment (50%). Mr. Chien-jung Yu is a Ph.D. student in Aerospace Engineering at ISU and is working on the numerical model of Litvina (50%).

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Figure 1. Horizontal profiles of normalized wind speed for various approach-wind incidence angles (IA), porosity of 50%, width of 0.5H, a) height of 0.1H, b) height of 0.7H.

Figure 2. Structure of individual-based models to estimate effects of climate change on populations of plants (top) and animals (bottom).

Observational and Numerical Study for Interannual and Interdecadal Variability of the Atmospheric Circulation

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Objective: The primary goal of this project is to examine effects of the Pacific sea-surface temperatures (SST) on the interannual and interdecadal variability of the winter and summer atmospheric circulation, and effects of doubling CO₂ on the interannual and interdecadal variability of the winter atmospheric circulation.

Approach: It was revealed by numerous studies that the long-term climate variabilities are reflected in variations of stationary eddies. For the observational study, we diagnostically analyzed the possible correlation between interannual/interdecadal variations of stationary eddies and climate variables at key locations, and performed the empirical orthogonal function (EOF) analysis of three variables. The purpose of these analyses was to explore the structure of interannual/interdecadal modes associated with stationary eddies. The data used in the observational study are OLR, COADS SST (Slutz 1985), upper-air data generated by the NMC Global Data Assimilation System (GDAS), and surface pressure-300 mb heights compiled by the NMC after World War II. For the numerical study, two types of numerical simulation with the NCAR Community Climate Model (CCM) (Williamson et al., 1987) were performed: (a) a real-time simulations with the 50-year (1943-1992) SST (from the COADS) and (b) a 30-year simulation with double CO₂.

The following tasks were pursued: (1) analysis of the three-dimensional structure of the interdecadal variation mode with the NMC data for the Northern Hemisphere and the Australian data for the Southern Hemisphere, (2) diagnostic analysis of the 50-year real-time SST simulation of the NCAR CCM to determine the effect of the Pacific SST on the interdecadal variation of the wintertime atmospheric circulation, (3) diagnostic analysis of observational data to explore the effect of the Pacific SST variation on the interannual variation of summertime stationary waves over the North Pacific basin, (4) interannual variation of the global relative

atmospheric angular momentum (RAM) and (5) the interannual variation of global RAM in the double CO₂ simulation.

Results to Date: The major findings related to the interdecadal variation of the Northern Hemisphere (NH)- wintertime circulation are summarized as follows: (1) The interdecadal variation of the NH winter circulation in the past four decades is associated with the amplification of stationary waves: the deepening of the three major stationary troughs and the weak amplification of the three major stationary ridges. (2) With some simple statistical analyses, two interdecadal variation modes were identified in the NH winter circulation: the so-called *Pacific* and *Atlantic* modes. The former mode exhibits a spatial structure similar to the Pacific-North America teleconnection pattern, while the latter mode possesses a spatial structure like the North-Atlantic Oscillation. Furthermore, although these two interdecadal modes are characterized by an equivalent barotropic structure, and have the same linear trend in their interdecadal evolution, they oscillate *independently*. The Pacific interdecadal mode oscillates coherently with the interdecadal mode of the North-Pacific SST. In contrast, the Atlantic interdecadal mode does not oscillate in a coherent way with that of the North Atlantic SST. (3) The Pacific interdecadal mode is associated with a meridional shift of the North Pacific jet stream and the associated cyclone activity of the Pacific storm track. The Atlantic interdecadal mode is associated with a slight meridional shift of the North Atlantic jet stream, but with enhanced cyclone activity only along the Atlantic storm track.

The major findings of the interdecadal variation of the Southern Hemisphere (SH) atmospheric circulation in the past two decades (1972-1992) are: (1) the interdecadal variation of the SH circulation in the past two decades was characterized by a latitudinal stratification in which the high-latitude circumpolar trough

deepened and the midlatitude high strengthened; (2) this interdecadal variation exhibited an equivalent barotropic structure; (3) the winter and summer spatial structure of the SH interdecadal variation persisted in the ensuing transition seasons; and (4) the cyclone activity was enhanced over the circumpolar low centers, following coherently their interdecadal deepening.

It is hypothesized that the interdecadal SST change is one of the possible mechanisms that can induce the interdecadal change of the NH winter circulation. To test this hypothesis, two multi-decade (1946-92) climate simulations were performed with the R15 resolution of the NCAR CCM1: one incorporating the 12 calendar month climatological SSTs, the other using the real-time SSTs. By contrasting the results of these two climate simulations, the effect of SST anomalies on the interdecadal change of the NH winter circulation was found to induce (1) the equatorward expansion of the circumpolar vortex, (2) the deepening of three climatological troughs, and (3) three interdecadal variation modes of stationary eddies: Pacific/North America (PNA), PNA west (PNAW), and North Atlantic (NA) modes. These three interdecadal modes were found to be equivalent barotropic in their vertical structure. Horizontally, both the PNA and PNAW modes exhibited a teleconnection pattern over the Pacific/North American region, while the NA mode possessed a north-south three-cell structure over the Greenland/North Atlantic region. The temporal variations of these three modes consisted of a decadal trend and 15-20 year low-frequency oscillations. The interdecadal variation of general circulation statistics is regulated by the interdecadal variation of the atmospheric circulation. In the thermal field, the transient heat flux diverges out of the warm anomalies and converges toward the cold anomalies. In the dynamic field, the cyclone activity over the midlatitude storm track region is affected by the variability of the north-south wind shear, which is induced by the equatorward expansion of the circumpolar vortex.

A teleconnection wave train (originating from the western tropical Pacific) along the northern rim of the Northern Pacific is evident from (1) the correlation coefficients between the upper-level height departures from the multi-summer mean and the SST anomalies averaged over the eastern tropical Pacific (NINO-3) region and (2) the composite charts of these upper height departures for the summers following the El

Niño-Southern Oscillation (ENSO) events in the past 15 years. This stationary wave train was separated into the long-wave (wavenumbers 1-3) and short-wave (wavenumbers 4-15) regimes. The long-wave train propagates from the western tropical Pacific to the Arctic along the western rim of the North Pacific. The short-wave train propagates from the northwestern Pacific to North America along the northern rim of the North Pacific. The long-wave train is related to the interannual variation of the East-Asian monsoon, while the short-wave train may be related to the interannual variation of the summertime North-American circulation.

The interannual variation of the global relative atmospheric angular momentum (RAM) coincides with the Southern Oscillation index and the NINO3-SST anomalies. This interannual variation of global RAM is coherent with the poleward propagation of RAM in the following manner. The global RAM reached its minimum values when westerly anomalies emerge in the tropics and higher latitudes, and easterly anomalies appear in the tropics during the cold-ENSO phase. The global RAM gains its maximum values when westerly anomalies arrive at the subtropics of both hemispheres and are strengthened during the warm-ENSO phase. It was demonstrated that the poleward propagation of RAM results from the flip-flop oscillation of the anomalous circulations between the cold and warm ENSO events.

Since the global RAM is a sensitive indicator of the interannual variation of the atmospheric circulation, this variable was adopted to illustrate the effect of doubling CO₂ on this interannual variation in the numerically simulated climates. We contrast the global RAM between the 30-year climate simulations with single and double CO₂ concentration using the NCAR CCMOA. Based upon the global RAM time series and the anomalous circulation patterns, we found that the interannual variation in the NCAR CCM climate can be enhanced by doubling CO₂.

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Other products

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Student participation:

Jau-Ming Chen 100% (the funding for this student's participation comes from a NSF grant).

Carbon, Water, and Energy Fluxes from a Tallgrass Prairie: A Long-term Investigation of Environmental, Biological, and Land Management Factors

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Objectives: Increasing concentrations of atmospheric CO₂ could have an enormous effect on biogeochemical cycling in the biosphere by inducing climate change and by directly affecting plant processes within ecosystems. Thus, understanding the factors that govern the earth C budget, and how these factors might respond to environmental permutations or changes in land

use, is vital if we are to prepare for the future. Unfortunately, long-term measurements of carbon, water, and energy fluxes from the Earth's major ecosystems are not available. Given that grasslands may compose up to 50% of the Earth's terrestrial surface, research on the magnitude and mechanisms of trace gas fluxes from this ecosystem is critical if we are to

quantify and predict the effect of climate change at regional or global scales.

The main objective of the experiment is to evaluate the flux of carbon, water, and energy from a tallgrass prairie over an extended time period, and determine the effect of environmental, biological, and land management (i.e., burning, grazing) factors on these fluxes.

Products: (1) An understanding of the relationships between the carbon and water budget, and how climate change and atmospheric CO₂ might influence these relationships; (2) Assessment of burning and grazing practices that affect the long-term carbon, water and energy budgets; (3) Examination of plant and soil processes that govern net carbon exchange from the prairie and how these processes can be scaled or modeled to evaluate the ecosystems role in a changing global environment (4) Estimation of the prairies role as a source or sink for atmospheric carbon; (5) Comparison of carbon and water exchange rates from the prairie with fluxes from other ecosystems?; (6) Assessment of measurement techniques for monitoring trace gas fluxes during long-term experiments; and (7) a historical database for the development and verification of regional biogeochemical models.

Approach: Meteorological stations will be established on the Konza Prairie Research Natural Area (KPRNA) that would provide continuous long-term (i.e., 10 yr.) measurements of CO₂, water vapor, and energy exchange. Measurement stations would be operated on three watersheds with differing land management regimes: (1) burned annually, (2) burned every four years, and (3) burned and grazed annually. Each measurement facility will consist of a 9m-tall meteorological tower, a small supplemental tower, underground bunker, and supporting equipment. The main tower will support a sonic anemometer, gas sampling intakes for conditional sampling and gradient methods, and other basic meteorological sensors. The supplemental mast will support a net radiometer and infrared transducer, so that the sensors will have an unobstructed view of the surface. The underground bunker will house the gas analyzers, data acquisition system, and supporting equipment (e.g., calibration gases, batteries, etc.).

The measurement stations have been designed

to provide accurate and redundant measurements of carbon and water flux while minimizing costs and maintenance. Carbon dioxide and water vapor fluxes from the surface will be initially measured using four different micrometeorological techniques, including: (1) Bowen ratio, (2) modified Bowen ratio, (3) conditional sampling (i.e., relaxed eddy accumulation), and (4) aerodynamic. During the first year of operation, research will be conducted to determine which method best suits the needs of the NIGEC project. Once a favored technique or group of techniques is determined, then that method will be used for the remainder of the study. Additionally, a wide range of other environmental parameters will be monitored, such as photosynthetic, global, and net radiation, wind speed, vapor pressure, temperature, and precipitation.

Measurement of several ancillary site attributes will provide supporting biotic and abiotic information on the underlying biophysical mechanisms affecting mass flux from the prairie. Supporting measurements can be categorized into carbon fluxes, water fluxes, vegetation, and soil components. Soil-surface CO₂ fluxes will be measured to help delineate plant and soil CO₂ fluxes and quantify the importance of soil respiration on the overall carbon budget. Measurements of leaf photosynthesis, leaf water potential, and sap flow will be used to explore the biophysical effect of vegetation on trace gas fluxes. Other measurements will include leaf area indexes, leaf nitrogen content, aboveground biomass, species composition, soil fertility, and soil water content.

Results to Date: During the first year of the project (FY 94), measurement locations were identified on an annual burn and 4-year burn watersheds within the KNPRA. Both sites are located in large lowland areas with representative vegetation and have ample fetch for the boundary layer measurements. Research permits were applied for and received. The vegetation at the sites was characterized and biomass data from previous research in the watershed was catalogued.

The underground concrete bunkers were fabricated and readied for installation. An attempt to install the bunkers in the February 1995 failed because the earth-moving equipment being used to excavate the bunker pits could not traverse the prairie when the soil was moist. The

bunkers will be installed in August or September of 1995.

The design of the instrumentation for measuring CO₂ and water vapor flux was finalized. Both Bowen ratio and Eddy accumulation techniques will be used simultaneously to provide a redundant and robust measurement of boundary layer fluxes. Additionally, every attempt was made to design a system that required minimal maintenance and did not have a large post-processing requirement. A prototype of the flux instrumentation was constructed as part of a study funded by the USDA titled Carbon and Water Fluxes From Irrigated Corn: A Field Scale Long-Term Study. This system will be evaluated over a fully developed corn canopy in the summer of 1995. Results from these tests will assist in the construction and operation of the NIGEC measurement stations.

Presentations:

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Student Participation: Dale Bremer 20%; Craig Sharp 50%.

The Economic and Environmental Impact of Major Shifts in Land Use into Energy Biomass Production for Part of the Great Plains

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Objective: A recognized need exist for alternatives to fossil fuel sources of energy which will reduce dependence on foreign oil, reduce emissions of CO₂ and provide an economically feasible and environmentally sound renewable energy source. One promising option is the use of biomass for energy production. Meeting this need could serve three important objectives of U.S. energy policy simultaneously: promoting the transition from nonrenewable to renewable sources of energy, mitigating the greenhouse effect, and assisting farmers in some agricultural regions in adapting to climate change.

This study addresses five questions: 1) Can woody and herbaceous biomass compete economically with traditional agriculture at the firm or farm level for the use of land and water resources under the existing climate? 2) What are the environmental impacts of large scale biomass production compared with those of traditional agricultural production? 3) How might CO₂ induced climate change affect the assessment of the economic and environmental feasibility of biomass since the process of substituting biomass for fossil fuels would occur gradually over several decades? 4) What would

the impacts be of large scale biomass production on the regional economy as a whole, and how would these effects compare with those of continued conventional agricultural uses of the region's land and water resources? 5) How might public perceptions of the environmental and health consequences affect achievement of the conversion to large scale biomass production both without and with climate change.

Product: The work proposed here will provide vital information to the determination of the impacts of climate change on the net systems of importance to human activity in the Great Plains. The potential for using large land area to produce biomass for energy is an issue which needs additional research. This study will quantify potential environmental and economic impacts. Environmental simulation and economic models can provide insight and improved understanding of alternative technology and policy for adapting to and mitigating possible future climate change.

Approach: The study has four principal parts: 1) An analysis of the economic and environmental characteristics of biomass production at the farm level relative to those of conventional agricultural practices in the region; 2) An analysis of the comparative economic and environmental characteristics when biomass production is expanded to the regional scale; 3) Analysis of the comparative regional scale impacts on the MINK (Missouri - Iowa - Nebraska - Kansas) economy as a whole; 4) An analysis of the difference climate change would make to the results of parts 1, 2, and 3.

The farm level analysis (part 1) is using the EPIC biophysical process model. The data sets developed for the MINK study (initially 30 farms) are being used as the base data for the case of conventional agricultural and biomass production. The regional analysis (part 2) is using the MINK watersheds from HUMUS (Hydrologic Model of the U.S.) to provide accounting of the regional impacts on the environment. The economic impacts (part 3) will use the ASM (Agricultural Sector Model) to address the regional economic impacts changes to biomass production. (This analysis will be done in years two and three of the study.) The Nested Regional GCM model will provide climate change data to study energy biomass production impacts under alternative climatic change scenarios (part 4).

Activities in year one (FY 94) have concentrated on part 1). In year two (FY95) we will address parts 2), and 3). In year three (FY 96) we will address the climatic impacts of part 4).

The EPIC model has been used to simulate both traditional crops and biomass energy crops on the scale of a farm field. The representative farm approach, outlined in the MINK study, was used to model both crops and biomass. The climate is being simulated using two (2) scenarios. Historical normal climate and 1930 s dustbowl climate. At a later date the dustbowl scenario will be replaced with climate change information from the GCM model. Data sets for thirty representative farms were spread across the four state area. The traditional crops scenario is being represented by rotations of corn, soybeans, sorghum, and wheat in various combinations depending on the practices found in the area.

For the biomass crop, switchgrass (*panicum virgatum* L.) was chosen for growth simulations on the same representative farms using the same climate and soils as was used in the traditional scenario.

To study the regional impacts of shifting land use from traditional crops to biomass energy crops on water use, water quality, runoff, erosion and other environmental indicators, the HUMUS model is being used for the watersheds of the four state region. To study the potential impacts of marginal increments of land use changes into biomass production, five scenarios are being set up to reflect the various levels of conversion. These scenarios will step from 0% to 80% of the cropland acres in biomass production in increments of 20%. Both EPIC and HUMUS allow the simulation of irrigation management on production acreage. Biomass production may impact the quantities of water in the watershed available for use on irrigated acreage as well as determining the impacts of increasing or decreasing irrigation on stream flows.

Results to Date: As of this report, the basic data sets for EPIC have been assembled and preliminary runs have been made on both traditional agriculture and switchgrass for biomass. Preliminary runs have been made on both the normal and dustbowl climates. The input and output numbers are being reviewed. However, it is premature to list those results at this time. Early indications are as expected.

Biomass production reduces both erosion and runoff. The preliminary results also indicate the climate scenario of the dustbowl may have a larger impact on switchgrass production than on traditional yields. However, no runs have not been made at elevated CO₂ levels utilizing the models ability to simulate evapotranspiration sensitivities to CO₂ levels.

Manuscripts and Presentations: The first year has been dedicated to obtaining the data and setting up the model runs, therefore no manuscripts or presentations have been written or given to date on this project.

Student participation: The first year of the project did not use students. Plans are to involve students in the crop simulation, watershed scenarios and regional economic analysis in the second and third years.

Regional Projections of C Dynamics with Global Change in the Central U.S.: Interactive Effects of Management, Climate and Elevated CO₂

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Objectives: The key objective of our research is to separate the interactive effects of climate, elevated CO₂ and management on soil organic matter (SOM) dynamics in the Central U.S. wheat and corn growing regions. We are applying a global change system analysis (Metherell 1992) to a benchmark database being developed as part of the Agroecosystem Science Program at Colorado State University. Another important objective is to provide information that can be used to design experimental studies to test the relative influence of these key factors of global change on soil C responses.

Products: We are producing information on projected SOM dynamics for widely distributed selected sites within the Great Plains of the central North America. To accomplish this we are determining (1) the effects of historical management practices, (2) future effects of current management, (3) effects of current management, with changed climate and CO₂ levels, (4) new management systems which optimize carbon storage and crop production within new climate/CO₂/management situations and , (5) the relative impacts of changed management, CO₂ and climate on agroecosystem C fluxes. This document reports the first of our publishable efforts resulting directly from NIGEC support (Elliott et al., in prep). We expect most of our publishable results to appear in the final year of the project.

Approach: We are using the CENTURY model (Parton et al., 1987) for our work, which is probably the most widely-applied SOM model currently available. The Century model environment has been extensively modified with a new file structure and a preprocessor called Event 100 (Metherell et al., 1993). Event 100 is used to schedule management events and the growth of different crops, and to control the overall execution of the Century model.

The updated Century model was used to simulate C and N dynamics (Metherell 1992) in innovative agricultural systems being field tested at three sites in eastern Colorado (Peterson et al., 1992). The long-term sustainability of the management systems was tested using the historical weather record for the localities of the field experiments. The effect of increased atmospheric CO₂ was tested by making appropriate adjustments to model parameters, while the effect of climate change was examined by either increasing the temperatures and adjusting precipitation amounts in the historical weather record or running the model with weather output from a mesoscale climate model. The results strongly suggest that with appropriate management for the prevailing environment, SOM levels in semiarid agroecosystems in eastern Colorado can be increased or at least stabilized (Metherell et al., 1995).

For our NIGEC project we are obtaining information for the products (listed above) through the following process:

- (1) Simulations using Century are being compared to the current status of agricultural systems based upon initial conditions before application of field treatments and the length of time the treatments have been in place.
- (2) Projecting future effects of current management allows us to determine the potential impact of a continuation of the current practices without the influence of global change.
- (3) We are projecting the effects of current management, with changed climate and CO₂ levels.
- (4) Model experiments to optimize management system for carbon storage and crop production are being conducted to determine (a) which of the possible management scenarios will result in the greatest storage of soil C (e.g., wheat-fallow vs. wheat-corn-fallow rotations) and (b) which of the possible management scenarios will result in the greatest crop production.
- (5) We are evaluating the relative impacts of management, CO₂, climate and their interaction on C fluxes. Of particular interest is (a) the comparison of the projection of the current management practices (see 2 above) with those same practices run under various climate change scenarios (see 3 above), and (b) comparison of current management under climate change (see 3 above) and new "optimized" management under climate change (see 4 above). Results from these two sets of comparisons allows us to make an assessment of the relative impacts of the direct effects of changing climate and the subsequent indirect effects of changes in management systems that may be better adapted to the new climate and CO₂ conditions.

Results to Date

Site Choice: We have made model-data comparisons for ten sites; four will be discussed here, (1) Sidney, NE and Sterling, Stratton and Walsh, CO. These sites were chosen to represent a gradient of increasing temperature (4°C difference in mean annual temperature north to south) with approximately constant precipitation. The result is a series of sites that span across a gradient of potential

evapotranspiration (PET), a key driver of ecosystem behavior in the Great Plains. Soil textures are generally similar but the Colorado sites have a longer history of cultivation (~60 years) than the Nebraska site, which has only been under cultivation for 20 years.

Model-Data Comparisons: Comparisons were made between model output and plant and soil data from the four sites. The data were obtained from a compendium of data from long-term experiments in North America (Paul et al., in press) and data obtained from samples we have taken at the sites based on another research project (Elliott et al., 1994a, Paustian et al., 1995). Analysis at each site consists of multiple steps (Elliott et al., 1994b). The model is run under native vegetation for 7,000 years, allowing SOM levels to reach steady-state for that set of climatic and edaphic driving variables. Then, each site was cultivated and cropped under historic management until the establishment of the agricultural experiment. The agricultural experiments, often with several treatments, are simulated until the present time and the results compared with existing plant and soil data.

Often, the only historical plant data are grain yields. Since grain yield is the result of a complex set of determinants, and often quite different in response from vegetative growth, matching grain yield data with Century grain yields is challenging. In addition, yields in the field are reduced by pests, hail and other acts of God whose mechanisms are not included in Century, which was primarily designed for analysis of SOM dynamics. Measurements of changes in SOM may be a better test for goodness of fit of Century to existing data. Soil SOM data are also prone to difficulties in sampling and measurement, although we have sampled all of the sites used in this report and feel confident in the results. The fit of simulated vs. observed SOM levels is somewhat better than for grain yield (Fig. 1). Some of the "luck of fit" of predicted to observed SOM levels is associated with uncertainty in the previous land-use history (since initial cultivation) at the sites as well as errors in the model estimates of soil C in the native soil prior to cultivation.

Model Analysis: For this report, global change-related variables consisted of alterations of total precipitation, the distribution of this precipitation over the year, temperature (represented by a north-south gradient of sites, Fig. 2), choice of

Figure 2. Precipitation (Monthly Average)

Figure 3. Grain Yield

Figure 4. Carbon Inputs

Figure 5. Change in Total Soil Carbon

cropping system, and elevated CO₂. With increasing adoption of no-tillage management in the Great Plains, more water is available for growth of crops (Peterson et al. 1993) and dryland corn may be successfully worked into the rotation in regions where corn has traditionally been not grown. At each site we simulated no-till management with wheat-fallow (WF), wheat-corn-fallow (WCF) or continuous wheat (W) with N limitations removed by fertilization. Water was varied by changing the total amount and distribution throughout the growing season. Precipitation was varied in each month from 40% to 160% of normal and the seasonal variations consisted of reducing the amount of precipitation during July and August by 0 to 60% and moving this water to May, June, and July. Thus, the water is essentially transferred from the hot and dry post-wheat harvest period, when water is likely to be lost to evaporation, to the wheat growing period. CO₂ was elevated to 700 ppm for some model runs.

Results: Precipitation amounts and distributions were similar across sites (Fig. 2) so differences observed in grain yields of wheat in the WF rotation are attributable to differences in temperature. Shoot and root residues entering the soil after harvest (C inputs) show generally the same pattern as grain yield, except that the response to precipitation was less steep (data not shown). Carbon inputs from all three cropping systems were similar at low precipitation levels. The WCF rotation, showing the greatest early response to precipitation but the W treatment had the greatest inputs at the highest precipitation level (Fig. 4, data for Stratton only shown). The WF treatment resulted in no change in SOM-C any site except Sidney, where the soil C losses increased with wetter conditions, probably because this site had a shorter history of cultivation (Fig. 5). Generally, SOM changes for WCF and W were similar at high precipitation levels but lagged behind in the W treatment under intermediate moisture levels, probably because there were relatively lower C inputs.

Increasingly shifting the precipitation from July and August to April, May and June resulted in greater SOM-C levels in the WF treatment (Fig. 6) probably because there were greater C inputs. The same was true to a lesser degree in the W treatment at lower precipitation levels, but the SOM-C levels in the WCF treatment showed no responses to rainfall redistribution (Fig. 6).

Elevated CO₂ resulted in large increases in SOM-C especially where wheat was grown (Fig. 7). Elevated CO₂ had the greatest influence in the continuous wheat at high precipitation levels. There did not appear to be an interaction between the timing of rainfall and cropping system on SOM-C levels (data not shown).

Conclusions: Alterations in cropping systems and elevated CO₂ appear to have a far greater impact on soil C levels than changes in climate under the current management systems. This means that a detailed analysis of the potential success of new cropping systems will be essential for evaluating the impact of global change on soil C sequestration in the Great Plains.

Acknowledgement: We would like to thank Serita Frey for preparation of the figures derived from model output.

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Figure 6. Change in Total Soil Organic Carbon at Stratton

Figure 7. Change in Total Soil Organic Carbon at Stratton

The Effect of Ecosystems on Cloud Microphysics and Aerosol Distribution

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Objectives: To examine changes of ecosystems of regional, national, and global scale in a changing climate. To evaluate the relationship between ecosystem and cloud cover, and the relationship between ecosystem, cloud droplet sizes, and total cloud liquid water content.

Product: (1) Construct NDVI distribution data on the basis of ISCCP analysis. We plan to construct a NDVI distribution dataset over continental areas covering five years (July 1986 - June 1991) on the basis of ISCCP analysis. This dataset will be on the near-global scale (50 S to 50 N). This process will rely upon ISCCP analysis for its cloud products (clear, cloudy categories for the same AVHRR pixel). Such a dataset will provide simultaneous information on NDVI indices and cloud cover. Once the ISCCP cloud products have been retrieved, the production of the NDVI indices requires only a minor increase in the processing requirements. (2) Perform near-global retrieval of cloud droplet radii. To study the effect of seasonal, regional changes of ecosystems on cloud microphysics, based on the previous work of Han et al. (1994), we are processing five years of ISCCP CX data to retrieve cloud droplet sizes (July 1986 - June 1991). This period avoids Mt. Pinatubo, covers one El Niño year, and provides coverage by two polar orbiters for all but the first five months. This will allow us to determine cloud droplet sizes appropriate for different ecosystems and seasons. (3) Estimation of effect of NDVI values on cloud droplet radii. This analysis will be performed by correlating distributions of NDVI values with cloud droplet radii. The relative importance of anthropogenic aerosol and ecosystem on cloud droplet radii will be investigated by comparing more polluted regions (e.g., eastern part of U.S.) with relatively clean regions (e.g., Great Plains).

Approach: Our analysis starts with the ISCCP cloud products retrieved from AVHRR data. These results include a division of individual fields-of-view (FOVs) into "clear" and "cloudy" categories and the retrieval of cloud optical thickness values. Only "clear" pixels will be used to calculate the NDVI, thus the cloud

contamination effect on NDVI can be easily minimized.

To complete the analysis of five years of AVHRR data, we are using the ISCCP CX dataset which is composed of the original radiances, sampled to about 30 km spacing, and the results of the ISCCP analysis, all at the original pixel level. Use of this dataset provides a statistical sample of the original AVHRR dataset, sufficient for producing a climatology of NDVI and cloud properties and takes advantage of the results of the ISCCP cloud detection analysis to provide an initial separation of image pixels into "clear" and "cloudy" categories.

There is no five-year period covered solely by one pair of AVHRRs; in all cases, we will need to pay close attention to intercalibration among the different AVHRR sensors. However, the NASA/NOAA PATHFINDER project is working to extend the ISCCP and other calibration results already available for Channels 1 and 4 on NOAA-7, -9, and -11 to the remaining spectral channels and to the AVHRRs on NOAA-6, -8, -10, and -12. We will be able to use these calibrations. The period selected, July 1986 - June 1991, is covered by NOAA-9 (February 1985 - October 1988), NOAA-10 (December 1986 - August 1991), and NOAA-11 (November 1988 - current).

The volume of this dataset is equivalent to six 6250 bpi data tapes per satellite per month. If dedicated processing were performed, then estimates of the CPU needed, together with tape and disk storage required, indicate that it is practical to analyze three satellite-months of data per week, requiring about nine months to process five years of data. However, once we develop the retrieval and analysis method, we can add our processing software to the other programs that will be running on the CX dataset during FY94 and 95. The resource demands of our software are smaller than those of the other analyses; but this may mean that the actual pace of analysis will be slower. This approach allows us to use the automated data handling facilities and software management system at the ISCCP

Global Processing Center at NASA Goddard Institute for Space Studies, which reduces the expense of the analysis to the marginal cost of some staff time and additional data tapes. This data processing will be performed at no cost to the project.

Results to Date:

Developing retrieval scheme

One of the ultimate targets of this proposal is to retrieve cloud droplet radii, NDVI, cloud amount at a near global scale for five years. The goal of year two of our research has been to develop retrieval scheme for the batch processing at GISS (Goddard Institute of Space Studies) ISCCP (International Satellite Cloud Climatology Project) processing center. To date, two years of data (January, April, July and October of 1987 and 1988, respectively), which have simultaneous retrieval of NDVI, cloud effective radius and cloud cover have been constructed. A production scheme has been developed and sent to ISCCP processing center to retrieve cloud properties and NDVI for the other three years. There is no problem with the time period of 1985 through 1988 which was covered by NOAA-9 satellite only. But started from 1989, NOAA-11 was the operational satellite and there are intercalibration problems for different channels between these two satellites. We are working on this now.

Result analysis

Another target of this proposal is to study the effect of ecosystems on cloud properties. The retrieved data of the two year period have been analyzed for this purpose. The results show that as an index of vegetation cover, NDVI has a positive correlation with cloud effective radius and cloud cover (see Fig. 1 for example) for most regions. This means that ecosystem affects both cloud formation and cloud properties, i.e., cloud formed more often at vegetation covered areas, and these clouds tend to have larger droplet sizes. The possible mechanism involved is that vegetation plays a role in increasing water vapor content and decreasing aerosol amount in the air. Thus resulted less CCN number density and larger amount of water vapor content lead to larger cloud droplet sizes. Further investigations at regional scales are being conducted currently.

We expect detailed relationship for specific regions.

Ecosystems have impact on aerosol distributions. Because aerosols are considered having direct and indirect effect on climate changes, we studied the hypothesized aerosol indirect effect by using the retrieved results. The results of variations of cloud droplet sizes are consistent with expectations for variations in aerosol

Fig. 1. Relationship between cloud amount and NDVI(x100) at 1.0°x1.0° grid box from -50°S to 50°N.

loading. Statistics shows that for most regions and most times, at 0.99 significance level, southern hemisphere clouds have larger droplet sizes than northern hemisphere clouds. But this interhemispheric contrast of cloud microphysics does not lead to a corresponding interhemispheric albedo contrast as speculated by theory of indirect effect of aerosols on climate change, which proposes that smaller cloud droplet radius will lead larger cloud albedo (referred as Twomey effect by some authors). The assumption used in indirect effect of aerosols is that cloud liquid water path (LWP) has to be held constant both spatially and temporally. In reality, LWP changes dramatically at both small scale and large scale. Regional studies also show that the difference of visible reflectances is negligible between polluted cloud and unpolluted stratiform clouds with droplet sizes differing by a factor of two. As a consequence, at a near global scale, an examination of the relationship between albedo and cloud droplet sizes reveals that for most

regions and most times, an indirect aerosol effect on climate is yet not detectable. However, three highly polluted regions (East coast of U.S., Europe, and Southeast China) appear to exhibit a local aerosol effect on cloud albedos.

Another analysis concerns the effect of ecosystem on surface temperature. We found a negative relationship between surface T_s and NDVI values on a near-global scale. This agrees with the local results reported by other investigators. Although it is hypothesized to be the result of fractional vegetation cover, a further investigation by using a larger data volume is needed.

Presentations:

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Impacts of Global Climate Change on Phytoplankton Productivity in Lakes Along a Thermal Gradient

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Objectives: The objectives for year two of the project were to (1) complete the DNA characterizations using RAPD-PCR, (2) analyze these characterizations statistically and to (3) characterize selected clones physiologically under a broad range of temperatures. This characterization will ascertain the thermal plasticity of these clones to determine the impacts of these adjustments or adaptations on primary productivity and higher trophic levels in lakes in the Great Plains.

Products: The products of year two are the genetic characterizations of 126 clones incorporating 154 bands from 5 primers. A cluster program was run on SAS statistical package and a dendrogram was generated from the Average Linkage Cluster Analysis. Thermal characterizations will be analyzed statistically using ANOVA.

Approach: The selection of clones to utilize in

the statistical analysis was made on the completeness of banding results by eliminating clones from the cluster analysis if bands were not generated in all of the primers. Freelance was used to translate the dendrogram based on the distance matrix from SAS cluster program.

The physiological temperature characterizations utilize the Turner Design Model 10-AU-000 fluorometer in nondestructive sampling procedures. Clones are kept in culture in 300-ml flasks in soil water medium augmented with Alga-gro nutrients (Carolina Biological Supply). Clones are acclimated to Pyrex borosilicate glass tubes with polypropylene screw caps for two 4-d periods with transfer of 10% volume between the acclimation periods and at the beginning of the complete growth sequence. Tubes were initialized to the various temperatures in gradual steps with a 4-d acclimation period to each temperature before the final analyses are attempted. Tubes were read daily during the

acclimation period and during the one-week run. Growth rates were calculated using the formula):

$$\text{Growth rate} = \frac{\ln(\text{fluorescence on day 1}) - \ln(\text{fluorescence on day 0})}{\ln(2)}$$

Results to Date: The goal of year two of our research has been to provide genetic information from the genetic markers generated during year one and to provide information on genetic variability among algal thermal ecotypes across a broad latitudinal temperature gradient traversing the Great Plains. A total of 126 clones have provided 149 different genetic markers with each of the five primers selected for statistical analysis. Genetic variation was quite large, with only three exactly duplicate marker patterns from all clones. Twenty-seven clusters were determined by the SAS Cluster procedure. Cluster patterns conform closely to state sampling locations, which is not surprising since the sampling sites have a disjunct distribution. The Texas clones cluster as a separate branch off the main cluster grouping and are thus the most distinct from the rest of the clones from the more northerly states. Other state locations cluster out into from two (Kansas) to ten South Dakota distinct clones. This variation is also a function of the number of successful isolates from the original sampling period and from the robustness of the individual clones in culture.

The genetic variation exhibited by the clones in the RAPD-PCR procedure is also mirrored in the thermal characterization procedures. Clones from the same geographical sampling site can show markedly different responses to the temperature regimes. These differences are shown in the growth response during the experimental period. The Texas clone depicted here shows an optimal growth rate in the temperature range from 26-29°C. The Manitoba clone shows optimal growth rate from 8-26°C and a steep decline at higher temperatures.

Presentations:

Jensen, Susan I., Raymond J. Lewis, Kyle D. Hoagland, Stephen G. Ernst, Virginia I. Miller and Dean M. DeNicola. 1995. Genetic variation in *Fragilaria capucina* clones along a latitudinal gradient. Phycological Society Meeting, Breckenridge, Colorado.

Publications:

Hoagland, Kyle D., Stephen G. Ernst, Susan I. Jensen, Raymond J. Lewis, Virginia I. Miller and Dean M. DeNicola. 1995. Genetic variation in *Fragilaria capucina* clones along a latitudinal gradient across North America: a baseline for detecting global climate change. Proceedings of the Thirteenth International Diatom Symposium in Diatom Research (in press)

Figure 1. Dendrogram showing relationships between groups of clones. Horizontal lines from the right show the relationship of clones generated from the Cluster procedure. Vertical lines along the left axis delineate locations of the various clusters. Clones tended to cluster by locations, but, apart from Texas and North Dakota, were closely related to each other.

Figure 2. Three representative clones showing highest growth rates for a one-week time period at six temperatures. In these clones, Texas (evenly dotted line) shows tolerance for the entire temperature range, but a maximum growth rate at the higher temperatures. Kansas, in the unevenly dotted line) shows good tolerance for the cooler temperatures, but a markedly decreased tolerance for the temperatures above 29°C. Manitoba, the northernmost clone, showed optimal growth rates at the lower temperatures, but died at the two higher temperatures.

Satellite Observation of Lake Ice as a Robust Indicator of Regional Climate Change

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Objective: The exploration of lake ice breakup as a spatially explicit climate indicator in the mid-to high latitude regions in late winter/early spring, the spatiotemporal region where temperature increases due to enhanced greenhouse warming are often predicted to be greatest. Realization of this objective is being effected via (1) satellite image analysis of lake ice breakup, (2) geostatistical and trend analysis of lake ice breakup patterns, and (3) implementation of a numerical thermodynamic lake ice model to simulate, via detailed sensitivity analyses, lake ice phenology under alternative climate scenarios.

Products: (1) Assemblage of relevant archival satellite (primarily GOES-VISSR) image data for a latitudinal transect (60 N, 105 W to 40 N, 85 W) including 81 large inland lakes and reservoirs in Wisconsin, Northern Michigan, Minnesota, North and South Dakota, and portions of Manitoba, Ontario, and Saskatchewan, Canada (Figure 1). (2) Development of a methodology for reliably and systematically determining ice-off

dates for those lakes large enough to be reliably resolved by the visible band (0.54-0.70 μm) of the GOES-VISSR, yet small enough to have a temporally distinct breakup date. (3) Satellite-derived ice-off dates for the 81 study lakes from 1980-1994, the period over which suitable metsat data were acquired and archived. (4) Provision of an initial basis for understanding both the climatic causes and limnological ramifications of observed variation in ice temporal dynamics and distribution. (5) Typification of the response of lake ice in the region given alternative meteorological forcing.

Approach: We are analyzing patterns of ice breakup on the resolvable rapid transition lakes in the study area (Figure 1) via satellite image analysis of archival metsat scenes. This analysis is based predominantly on both visual and automated classification of more than 2000 GOES and AVHRR images of the region. The assembly, preprocessing, and analysis of this huge (> 8 GB) data set has been an important focus of the study to date. Our earlier work suggested both the feasibility of using the

AVHRR to determine the date of lake ice breakup as well as the strong correlation of the AVHRR-derived ice-off date with local air temperature (Wynne and Lillesand 1993), and data from this sensor continues to be a supplemental data source. However, we have relied principally on comparatively lowcost digital GOES data from the national archive (held by the Space Science and Engineering Center of the University of Wisconsin-Madison).

Our examination of the relationships among the spatiotemporal variability in climate, lake morphology, and lake ice phenology is based upon both statistical analyses (e.g., Wynne et al. 1995) and process-based modeling (e.g., Vavrus and Wynne 1994, Vavrus et al. 1995). The former is predicated on (1) determining the extent to which the response of a single lake can serve as a regional climate proxy, (2) assessing the presence or absence of any trends in the data both in space and time, and (3) attributing any observed trend in time and/or space to attendant causes (in concert with the process-modeling component).

We found temporal coherence, the degree to which different locations within a region behave similarly through time (Magnuson et al. 1990) to be a useful means of assessing the degree to which one can generalize site-specific findings to the surrounding region. We calculated the temporal coherence of ice-off dates (1987-1994) between each lake-pair by taking the product-moment correlation between their 8 year time series (1987-1994) of ice-off dates. The 62 lakes used in this analysis generated 1891 lake-pairs ($62 \times 61 - 2$). Ice breakup dates do not appear to be autocorrelated, thus it was unnecessary to lag the time series and re-compute coherence. We determined the significance of the determinants of temporal coherence of lake ice-off dates as well as the determinants of mean lake ice-off dates via a randomization test written in Matlab. For the coherence analysis we randomly selected completely independent lake-pairs, such that any lake represented in a particular lake-pair was not present in any other lake-pair. While this would not completely remove any possible spatial dependence among observations, it could help to reduce considerably dependence among correlation values (Wynne et al. 1995).

An important goal of this study is the assessment of any trend toward earlier or later ice-off dates

during the study period. As noted, ice-off dates do not seem to be serially autocorrelated. However, the spatial distribution of the mean ice-off date is far from stationary. In our ongoing analysis, we first remove as much of the spatial pattern as possible through the use of appropriate explanatory variables. This then affords us the possibility to examine the data set for temporal trends.

Process-based modeling provides a rigorous means to determine the climate sensitivity of lake ice, as well as how this sensitivity may be tempered by lake morphology. We have utilized the numerical thermodynamic lake ice model LIMNOS (Lake Ice Model Numerical Operational Simulation) described by Vavrus et al. (1995). The input variables required to drive LIMNOS are mean lake depth, air temperature and moisture, wind speed, solar radiation, snowfall, and cloudiness. These variables (excepting cloudiness) can be altered systematically to determine the sensitivity of any lake ice property (thickness, ice formation date, ice breakup date, etc.) to any type of climate change and to variations of lake depth. Hourly data obtained from the NOAA National Climatic Data Center Solar and Meteorological Surface Observation Network (SAMSON) from 1960-1990 were used to drive LIMNOS. Subsequent to exploration and testing in this historical context, Vavrus et al. (1995) performed a detailed sensitivity analysis to quantify the effects of altered meteorological forcing on the thermodynamics of lake ice.

Results to Date:

Assembly, Processing, and Analysis of Archival Satellite Data

As noted in the previous section, the assembly, processing, and analysis of the enormous (> 8 GB) satellite digital data set has been an important focus of the study to date. We have now completed the assessment of all 1830 GOES-VISSR scenes. These images were acquired at or near 19:00:00 coordinated universal time (UTC) on a daily basis from March 1 to June 30, 1980-1994. With the knowledge that these data are important deliverables in and of themselves (and will be an important archive beyond our project lifetime), we have paid careful attention to both appropriate preprocessing and metadata. To the latter end, we are using the Borland Paradox relational database to store both reduced browse imagery and relevant metadata. Paradox fields for the GOES data set

include, for example, the original archival file name, Erdas file name, name of the destripped image, sensor source, date, day number, UTC time, number of rows and columns, number of bands, byte order, banding angle, etc. We are fortunate to have a CD-ROM recorder in-house, and plan to make CD-ROMs of the project metadata as one of our final products.

Preprocessing of the GOES digital data presents problems not encountered with the AVHRR data set, notably extensive striping (caused by the differences in gain among the sensor's eight photomultipliers in addition to substantive quantization error due to the 6-bit radiometric resolution). In this regard, we are fortunate to have collaborated with Dr. Frank Scarpace (UW-Madison Environmental Remote Sensing Center), who has tailored his fast Fourier transform (notch) filtering software for the needs of this project (Wynne et al. 1995).

Visual interpretation was performed in a temporal context, in which ice-off dates were determined relative to ice conditions on proximate days. Major constraints were cloud cover, the poor spatial and spectral resolution of the GOES-VISSR, and the difficulty in distinguishing bare ice from open water. Comparison to available ground-derived ice breakup dates revealed a mean absolute difference of 3.2 days and a mean difference of -0.4 days (Rodman et al. 1995).

Determinants of Temporal Coherence of Ice Breakup Dates

The remotely-sensed ice breakup dates from 1987-1994 for 62 of our study lakes were analyzed to assess preliminarily determinants of the mean date of lake ice breakup and to identify determinants of temporal coherence of lake ice breakup (Wynne et al. 1995). The mean thaw date was day number 116 (given January 1 is day number 1 in a particular year). The range was from day number 80 (Lake Geneva, Wisconsin) to day number 170 (Etawney Lake, Manitoba). Correlations among the mean breakup date and the explanatory variables (surface area, maximum depth, surface area/maximum depth ratio, latitude, longitude, and elevation) revealed that only latitude ($r = 0.9603$, Figure 2) and surface area ($r = 0.4535$) were significant at $p \leq 0.05$. Latitude and surface area were significantly correlated ($r = 0.4173$) (Wynne et al. 1995).

The temporal coherence of ice-off dates between each pair of lakes was calculated by taking the product-moment correlation between their 8 year time series (1987-1994) of ice-off dates. The mean coherence was 0.4493, with values ranging from -0.8751 to 0.9996. There is a general lack of strong temporal coherence among lakes, implying that no lake within this study area is representative of the entire region. The significant ($p \leq 0.05$) correlates of the temporal coherence of ice-off dates were the difference in mean ice-off date (-0.4948) and the difference in latitude ($r = -0.5129$), themselves significantly correlated ($r = 0.8926$). The differences in surface area, maximum depth, surface area/maximum depth ratio, longitude, and elevation were not significant. The general lack of strong temporal coherence between lakes and the significant correlation between coherence and the mean ice-off date are further confirmation that ice-off dates for different lakes may be reflections of (and indicators for) different periods of meteorological forcing. Temporal coherence of ice breakup dates may prove to be one important means of determining the subset of lakes that can serve as proxies for each other and for the late winter and early spring climate in a particular region (Wynne et al. 1995).

Adaptation and Application of Climate-Ice Physics Model

LIMNOS simulates the growth and decay of lake ice by time-integrating the vertical heat conduction equations for layers of ice and snow. An energy balance at the ice and snow surfaces is assumed, such that the sum of incoming net shortwave and longwave radiative fluxes as well as sensible and latent turbulent heat fluxes are balanced by vertical heat conduction through the ice and snow layers. Implementation of this model for Lake Mendota using hourly SAMSON data from 1960-1990 produced quite realistic ice freeze (RMSE of 3.5 days) and thaw (RMSE of 5.4 days) dates (Vavrus et al. 1995). These errors are much smaller than the range of natural variability of both ice-on ($\bar{I} = 10.0$ days) and ice-off ($\bar{I} = 11.8$ days) dates during this period. Extensive sensitivity tests of this model reveal (1) the ice-off date is more sensitive than the ice-on date to air temperature changes (Figure 3), (2) the sensitivity of both ice-on and ice-off dates is greater for climatic warming than cooling (Figure 3), (3) increased snowfall produces a monotonic delay in the simulated breakup date (Figure 4), and (4) decreased snowfall leads to a non-linear

acceleration of ice decay (Figure 4). (Vavrus et al. 1995).

References/Reports/Presentations:

Rodman, D.C., R.H. Wynne, and T.M. Lillesand. 1995. An assessment of the GOES-VISSR for determining lake ice breakup dates: Implications for operational monitoring. Technical Papers, International Society for Photogrammetry and Remote Sensing Workshop on Mapping and Environmental Applications of GIS Data, Madison, Wisconsin (in press).

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Vavrus, S.J., R.H. Wynne, and J.A. Foley, 1995. The sensitivity of southern Wisconsin lake ice to climate change and lake depth using a numerical model. *Limnology and Oceanography* (in review).

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Wynne, R.H., D.C. Rodman, J.J. Magnuson, and T.M. Lillesand, 1994. Coherence of lake ice thaw dates on the Laurentian Shield as influenced by location and size as an indicator of regional climate change. ASLO/NABS Symposium, Freshwater Ecosystems and Climate Change in North America: A Regional Approach, Leesburg, VA, October 24-28, p. 34.

Student Participation: Randolph H. Wynne, Graduate Research Assistant, 50% and Daniel C. Rodman, Undergraduate Project Assistant, 20%.

Figure 1. Map of study area showing general locations of the 81 study lakes and reservoirs. Map source: Digital Chart of the World.

Figure 2. Satellite-derived mean ice breakup date (1987-1994) as a function of latitude for our study lakes. This relationship is highly significant, with $R^2 = 92\%$, $p = 0$, and standard error = 6.4 days (Wynne et al. 1995.)

Figure 3. Simulated change in the dates of ice formation and breakup for Lake Mendota due to changes in mean annual air temperature. Note the greater sensitivity of the ice-off date (Vavrus et al. 1995).

Figure 4. Effect of snowfall rate on the simulated ice-off date of Lake Mendota. When snowfall is reduced more than 50%, the increased conductive heat loss associated with less snow cover mitigates the enhanced surface ablation that accompanies a thinner, less persistent snow pack (Vavrus et al. 1995).

Scaling in a Spatially Explicit Model of Ecological Response to Global Change

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Objectives: Spatial scaling affects the response of computer simulations of vegetation to fragmentation, barriers, and corridors in the landscape during periods of climatic change. We use a computer simulation model of the dynamic processes of dispersal, establishment, growth, and death of forest trees in a spatially explicit framework to show that the spatial configuration of landscapes controls their reproduction. Three general factors are studied that affect forest dynamics and structure: climatic range, dispersal abilities, and spatial structure. In this research we implement a multi-cell simulation in which we systematically alter the areas represented by each cell in order to elucidate the problems of scaling spatial pattern and process in simulations. The objective of this research is to investigate the consequences of changing the spatial scale of representation of a multi-cell grid model from the landscape to the regional level.

Products: (1) An understanding of the relative

effects of the length of an environmental gradient of climate included in simulations. (2) An understanding of the effects of the step size in an environmental gradient for gradients of different lengths. (3) Identification of the effects of different kinds and degrees of landscape fragmentation on simulation results. (4) An outline of steps needed to incorporate refined information on species dispersal in fragmented landscapes into models at progressively coarser spatial resolutions.

Approach: Our modification of the JABOWA-FORET simulation model, the Module Of Spatially Explicit Landscapes (MOSEL) is used as the principle vehicle for conducting simulation runs. Several factors are held constant through all runs: the initial conditions and the amount of climatic change are constant, except for the control case of no climatic change. The standard inputs for tree species adaptations will be used in a modified form. The original model

represented a single 10x10 m stand of trees. We use these stands to represent a surrounding area of forest. For this research we begin with a 64x64 cell grid. Each simulation is run for 500 yr. and includes 75 of the dominant tree species of eastern North America.

Over this grid we superimpose an initial north-south gradient of growing degree days (GDD; summed above 4.4o C base) and an east-west gradient of moisture. For the longest gradient the coldest row begins with a mean of 600 GDD while the warmest is at 5600. The west - east gradient is given by the simulation parameter WILT ($WILT = (PET - AET) / PET$), which we change from a 0.10 to 0.01 for the longest gradient. For a short gradient the range of degree days is 1850 to 4350 (WILT remains the same). For a trial with no gradient all cells are given a degree day level of 3100 and WILT of .05.

Our method uses a series of dispersal rules that apply to the major dispersal types: gravity, wind, and animals. Considering a range of dispersal types is important because it allows us to examine different responses to scale change. To simulate dispersal by gravity we assume that any species producing seed on a site will have potential replacement on that site. Wind dispersal is modeled as a negative exponential decay away from each source cell. Zoochory is also modeled using a probability given by a negative exponential decay away from source cells for three types, which we conceptualize as mammal, scrub-bird, and bluejay. For each plot the simulation model calculates whether a seed source is extant based on presence of individuals of reproductive age by species and probability of a seed crop in a given year. The model then calculates the seed rain to surrounding plots.

In order to assess the effects of different dispersal distances as well as different amounts of environmental change across the grid, it was necessary to obtain improved estimates of the dispersal functions of the species. We analyze the effects of dispersal probability ($p = cd^a$), generation time, seed crop probability, and varying proportions and patterns of landscape fragmentation on migration rate. Comparisons are made with rates inferred for migrations based on isopols of species range changes in the Holocene. We began with a 5,000 cell transect representing 10 x 50,000 m continuous plane of forest, but with trees only on the first cell; in successive runs we fragmented this grid in the

following ways: regularly fragmented, with every third cell uninhabitable or every third cell habitable; randomly fragmented, with 1/3 and 2/3 cells uninhabitable; or containing a continuous barrier in the middle with 100, 200, 400, or 800 cells uninhabitable (the barriers are 1, 2, 4, or 8 km). The number of years until trees reached the end of the transect was used to determine the mean migration rate ($m \text{ yr}^{-1}$) for the 25 replicate runs of each combination of parameters.

Results to Date: The results for increasing the length of the gradient indicate that the amount of environmental difference represented in a grid affects the outcome. We analyzed the species diversity predicted by the model. With no gradient, only 3 species are extant in the entire grid (gamma diversity) and the mean diversity per cell (alpha diversity) is 1.36 (Figure 1). With a short gradient, the gamma diversity is 14 and the alpha diversity is 3.08 (Figure 2). With a long gradient the gamma diversity is again 14, but the mean alpha diversity is 2.58 (Figure 3). With no gradient diversity is limited because few species are highly adapted and competitive for the chosen environment; for the short gradient diversity is high because more species can be accommodated and for those species more cells with a similar habitat are available; for the long gradient, although more species can be accommodated, each cell is more distinct from the others and the possibility of extinction for narrowly specialized species is greater; alternatively, the long gradient may be species poor because it contains more of the coldest area simulated, which supports fewer species.

When cells are grouped so that the environmental gradient in either directions is represented by 64, 16, and 8 steps (Figures 3, 4, 5), the effect on diversity is negligible. One can see a pattern developing along the gradient of degree days, but it is not expressed in the summary diversity results.

For the simulations of migration rates, the effects of dispersal probability are revealed in graphs of migration rate over the exponent a for the alternative conditions simulated (e.g. Figure 6). Differences due to generation time and fragmentation are greater at the higher dispersal probabilities; at low probabilities absolute differences, although small, are still distinct. The effects of fragmentation are variable (Figure 7). In general, 1/3 fragmentation in both a random

and regular pattern lowers the migration rate slightly. At 2/3 fragmentation the effect is more distinct. The additional effect is greatest with shorter generation times. The effect of single large barriers is not seen for small barriers, and at up to 4 km no difference in rate is seen. The barrier effect does become distinct at 8 km, but the pattern revealed is unexpected. With the smaller barriers, slight differences from the continuous case are seen at the higher exponents, and, as with the other variables, effects are masked where the dispersal probability is low. With the larger barrier, however, the absolute effects, while slightly greater at the higher dispersal probabilities, are also clear at the lower ones.

To adjust these rates for different lengths of environmental gradients (and thus distances) represented by the step from cell to cell will require additional research. We have begun to examine how much the migration rate will change if the distances are altered. The probability of dispersal cannot simply be reduced by the same proportion that the distance is increased (i.e., halving the probability for a doubling of distance does not produce the same rate). We have identified the complexity and degree of difference in order to derive an single function for altering dispersal probability for given inter-cell distance.

Manuscripts in preparation, in press, and submitted:

Malanson, G.P. Effects of dispersal and mortality on diversity in a forest stand model. *Ecological Modelling*, in press.

Malanson, G.P. & Cairns, D.M. Effects of dispersal, population delays, and forest fragmentation on tree migration rates. submitted to *Journal of Biogeography*.

Malanson, G.P., Cairns, D.M. and Armstrong, M.P. Scaling in a spatially explicit ecological model. in preparation.

Presentations:

Malanson, G.P. & D.M. Cairns. Calibrating dispersal in a simulation of fragmented forest dynamics. U.S. Landscape Ecology Symposium, Minneapolis, April, 1995.

Student participation: David M. Cairns 50%.

Figure 1. Diversity on the grid with no gradient.

Figure 2. Diversity on the grid with a short gradient (64 steps).

Figure 3. Diversity on the grid with a long gradient (64 steps).

Figure 4. Diversity on the grid with a long gradient grouped into 16 steps.

Figure 5. Diversity on the grid with a long gradient grouped into 8 steps.

Figure 6. Migration rate varies for dispersal probability exponent and generation time.

Figure 7. Migration rate varies little for different types of fragmentation.

Modeling the Effect of Global Change on Grassland Distribution and Productivity at Landscape to Regional Scales

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Objectives: The main objectives of our research are to assemble and implement a linked MAPSS/CENTURY modeling system in the central grasslands region, and assess effects of changes in climate and disturbance on grassland vegetation and ecosystem function at landscape to regional scales.

The proposed research seeks to answer two questions: (1) how will hydrology, nutrient cycling, and disturbance interact with climatically-induced changes in forest and rangeland distribution to alter water and energy fluxes; and (2) do simulations of climate-induced vegetation changes produce similar predictions of altered forest and rangeland distribution and water and energy fluxes when calculated at scales ranging from 50 m up to 50 km?

Ecosystems are not likely to move as a unit in response to climate change; rather, individual functional groups (e.g., C_3 and C_4 grasses or trees) will probably disassociate, reassembling in new combinations. It is therefore likely that the anticipated change in the global climate will have direct, complex impacts on ecosystems across the country. Changes in these biotic assemblages will, in turn, modify ecosystem properties that regulate the release and uptake of many "greenhouse" gases, as well as control the hydrology and surface energy balances. These processes are critical determinants of our global climate, and insufficient attention has been paid to the ways in which these biological attributes interact with global processes, and the scales at which these interactions operate.

Products: A complete series of environmental datasets suitable for use in a wide range of hydro-ecological modeling activities will be generated for Wind Cave National Park. These datasets will include two water years of mapped daily climatic parameters, as well as soils and vegetation maps. A fully calibrated, hybrid MAPSS/CENTURY model will be assembled. The model will provide state-of-the-science

assessments of the effects of future climate and disturbance regimes on grassland vegetation and ecosystem function at landscape to regional scales in the central grasslands region. At least two journal articles describing the methods and results from this project will be prepared and submitted to peer-reviewed journals. Included will be an article describing the results from applications of the MAPSS/CENTURY hybrid to standard $2\times CO_2$ scenarios from GCMs, and more regionally accurate scenarios derived from applications of the RAMS model with GCM boundary conditions (being conducted as part of another project).

Approach: Wind Cave National Park is the primary test site for this modeling project because of the diversity of plant communities and the availability of research data from ongoing and past research studies. The area is primarily a mixed grass prairie with ponderosa pine covering many of the bluffs and interdigitating with the prairie. The topographic setting is of rolling hills with elevations ranging from 1090 to 1530 m. The distribution of forest and grassland communities appears to be determined by soil depth and moisture conditions. Fire and grazing regimes also play an important role in determining the establishment and composition of the plant communities.

Development of landscape-scale environmental datasets: A digital terrain grid, or digital elevation model (DEM) of the Wind Cave area will serve as a base map. Gridded model inputs of climate (i.e., monthly and daily temperature, precipitation, vapor pressure, wind speed, and solar radiation) will be generated for the Wind Cave area for water years 1993 (October 1992 - September 1993) and 1994 (October 1993 - September 1994). This period encompasses the two field seasons of CSU field data collection, which will provide important vegetation data for model calibration and evaluation.

Model assembly, calibration, and evaluation for

landscape and regional scales: We envision the coupling of MAPSS and CENTURY proceeding in three steps. The first step will be a loose coupling of the models. Separate applications of 1-D MAPSS and CENTURY will be made to the central grasslands region for current climate and selected future climate scenarios, with the biogeographical output from MAPSS providing a vegetation type for CENTURY. The next step will be the implementation of selected CENTURY modules into MAPSS-Watershed (MAPSS-W). Of highest priority are modules for determining growth rates of tree, shrub, and grass life forms, and hydrologic algorithms. The final step will be to link 1-D MAPSS and CENTURY for regional-scale assessments.

Assessment of climate and disturbance impacts:

The MAPSS/CENTURY hybrids will be applied to various scenarios of climate change and disturbance regimes at landscape and regional scales. The objective will be to identify the relative importance of different climate and disturbance parameters in producing changes in modeled vegetation and function at varying scales.

Results to Date: As part of his Ph.D. dissertation work, Christopher Daly completed the initial development and calibration of MAPSS-W (MAPSS-Watershed), capable of simulating the three-dimensional transport of subsurface water in small catchments. The model was calibrated and evaluated over two water years in the Reynolds Creek watershed, a USDA-ARS (Agricultural Research Service) basin located in the Owyhee Mountains of southwestern Idaho. Results indicate the model does an excellent job of predicting non-woody leaf area, daily runoff from the basin, and other hydrologic features. MAPSS-W and CENTURY will be linked for landscape-scale assessment of climate change effects at Wind Cave National Park.

The preparation of environmental datasets for Wind Cave National Park is largely complete. Monthly maps of minimum and maximum temperature, precipitation, vapor pressure, wind speed, and solar radiation were prepared for WY93 and WY94. Daily maps were developed using the monthly maps as bases, and treating the daily variations as anomalies or proportions of the monthly values. This method was used successfully by Daly (1994) at Reynolds Creek. Climate data for the park were extremely limited,

with only precipitation and temperature available at park headquarters. Data for other parameters were obtained from stations in the Black Hills region, drawing heavily on observations from Rapid City. Thus, methods used for mapping climatic parameters were necessarily simple, but sensitive to the topographic diversity in the park whenever possible. Emphasis was placed on simulating the complex radiation and temperature regimes, which are thought to contribute to the patterns of vegetation in the park.

DEM: A digital elevation model (DEM) with a cell size of 50 m was obtained from the EROS Data Center to serve as a base map. The DEM was checked for accuracy and registration problems by overlaying USGS stream networks. A modeling region encompassing Wind cave and vicinity was selected, and measures 17 x 21 km.

Precipitation: Daily precipitation data were available at park headquarters. A qualitative sense of the patterns of precipitation elsewhere in the park was obtained from temporary raingauges operated for a short time in the summer of 1993 as part of the National Biological Service CEGR-1 project. Although very spotty and uncertain, the measured precipitation patterns appeared to be responding to broadly-defined terrain features with a scale on the order of 4 km. This large-scale response pattern had been observed previously in PRISM precipitation modeling work in the western U.S. (Daly et al. 1994). To provide a suitable base terrain grid for precipitation mapping, the 50-m DEM was smoothed to an effective scale of 4000 m using a modified Barnes (1964) filter. The CEGR-1 network was used as a rough guide for determining an approximate relationship between the smoothed DEM elevation and precipitation across the park. Setting precipitation at headquarters at 100% each month, precipitation varied from 85% in the low terrain to the southeast to 120% in the mountains to the northwest.

Solar Radiation: No data were available in the park. The radiation climatology for flat sites was approximated with data from Rapid City (Caputa). However, radiation varies appreciably over the park as a result of the variety of topographic exposures. This variability was simulated by calculating direct and diffuse beam radiation for each pixel, accounting for pixel orientation, slope, surrounding horizon and ratio of diffuse to direct beam radiation (Frew, 1990).

The ratio of diffuse to direct beam is a function of atmospheric transmissivity, usually due to cloudiness (Bristow and Campbell 1984). Transmissivity was inferred from the difference between actual daily radiation in Rapid City and a hypothetical "clear sky" radiation (Frew, 1990) at the same location. Resulting maps of total radiation in the park show that on clear, summer days, shady north slopes received up to 40% less radiation than sunny south slopes.

Temperature: Temperature data in the park were available at headquarters. Regional lapse rates of minimum and maximum temperature with elevation were determined through a piecewise linear regression of measurements at Hot Springs (low elevation, 25 km south), park headquarters (middle elevation), and Custer (high elevation, 25 km northwest). The regional lapse of temperature with elevation was strongly negative in spring, summer and fall, but was typically flat or positive during wintertime inversion events. In addition, local maximum temperature is thought to vary as a function of small-scale, topographically-driven variations in direct solar radiation. Based on empirical data, shady, north-facing slopes were assumed to have a maximum temperature of up to 2.5 degrees C cooler than a level pixel at the same elevation, with sunny, south-facing slopes being up to 2.5 degrees C warmer. Minimum temperature does not appear to vary in a predictable way on different slope exposures (Running, 1985). Topographic differences in temperature were greatest in summer and least in winter, because of the comparatively large incident energy available in summer.

Wind Speed: No wind speed data were available in the park. Measurements at Rapid City (Caputa) were used as wind speed estimates throughout the park. A wind model would have been necessary to characterize wind flow patterns in and around the terrain features of Wind Cave, but such modeling was out of the scope of this study. Mean daily wind speeds were typically greatest in the winter and spring (4-8 m/s), and least in the summer (1-5 m/s).

Vapor Pressure: Daily relative humidity was estimated from measurements at Rapid City (Caputa), and used in conjunction with mean daily temperature (average of maximum and minimum temperature) to calculate vapor pressure for each pixel in the region (Frew, 1990). Vapor pressure ranged from less than

400 Pa in winter to over 1250 Pa in summer, and tended to be lower in the northwest mountains due to lower temperatures.

Woody Leaf Area: Woody LAI was estimated using Landsat multispectral scanner (MSS) images of the area obtained from the EROS Data Center. A MSS band 5 image taken on 22 June 1973 corresponded well to the distribution of forest cover in the region. Using the forest cover shading on a topographic map as a guide, the approximate band-5 reflectance that matched the forest/no forest boundary was estimated and a raster "mask" of forested areas constructed. For areas having forest cover, functional (all-sided) woody LAI was estimated using NDVI – $(\text{band } 7 - \text{band } 5) / (\text{band } 7 + \text{band } 5)$ – from the same June image. The NDVI was scaled to LAI by setting the forested pixel with the highest NDVI to an LAI of 8 and the forested pixel with the lowest NDVI to an LAI of 2 (Kaufman et al. 1982).

Soils: A map of soil associations for the park was obtained from the STATSGO (Soil Conservation Service) soils database. This are currently being combined with soil pit data taken in the CEGR-1 field project to produce raster maps of soil depth and texture.

Presentations:

Daly, C. 1995. Modeling climate, vegetation, and water balance in the Reynolds Creek watershed. Presented at the USDA Agricultural Research Service Northwest Watershed Research Center, Boise, ID, June, 1995.

Daly, C. and R.P. Neilson. 1995. Spatially-explicit simulation of climate-induced leaf area and water balance in a small, mountainous watershed. Presented at the annual meeting of the Association of American Geographers, Chicago, IL, March, 1995.

Daly, C. and R.P. Neilson. 1995. Update of landscape-scale modeling activities in the DOE-NIGEC project. Presented at the annual meeting of the National Biological Service Central Grasslands Global Change project, Fort Collins, CO, January, 1995.

Daly, C. 1994. Modeling climate, vegetation, and water balance at landscape to regional scales. Ph.D. defense seminar, Oregon State University, September, 1994.

Daly, C. and R.P. Neilson. 1994. Landscape-scale simulation of climate-induced water balance and vegetation distribution in the Reynolds Creek watershed, Idaho. Presented at the annual meeting of the Ecological Society of America, Knoxville, TN, August, 1994.

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Development of a Nested Regional Model for the Conterminous U.S. and Formation of High Resolution Climate Change Scenarios with an Application to Crop-Climate Models

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Objectives: The overall objective of our research is the development of a nested regional model for the U.S. and formation of high resolution climate change scenarios with applications to a series of crop models in the central Great Plains region. This work will lead to a greater understanding of possible changes in climate in the central Great Plains and to better understanding of resulting impacts on crops. In the second year we proposed to further improve RegCM2 to overcome biases found in runs produced the first year, produce and analyze a multi-year run using European Center for Medium Range Weather Forecasting (ECMWF) boundary conditions, evaluate several

general circulation models as candidates for providing boundary conditions for a control and doubled run of the regional model, and continue crop model testing with observed climate data at Nebraska and NCAR. The objective of the crop modeling procedures is to provide a method for determining whether higher spatial resolution climate change estimates than available from GCMs improve or otherwise cause substantial revision of the crop yield impacts simulated with GCM data.

Products: 1) Improved version of the NCAR RegCM, which will be made available to the scientific community. 2) High spatial and

temporal resolution model output of all relevant climatic and surface variables over the U. S., centered on the Great Plains, for the ECMWF-driven validation run (and in year three for the control and doubled runs). 3) Testing of different types of crop models (e.g., EPIC, CERES) and scaling of simulated crop yield output at different spatial scales.

Approach: As described in the progress report at the end of year 1, a multi-year validation run revealed a number of model biases, such as a too dry lower boundary layer and excessive summer precipitation. The biases were so large that it was deemed necessary to reduce them before proceeding to the completion of climate simulations.

Model development aimed at the reduction of these biases thus became a major focus for the second year. The lower boundary layer dry bias was mostly caused by excessive vertical transport of moisture and subsequent detrainment from the boundary layer. We modified the vertical profiles of moisture diffusivity during daytime convection based on diffusivity profiles (by Wyngaard). The new diffusivity values are smaller than in the original model scheme in the lower boundary layer and significantly contributed to decreasing vertical moisture transport and reducing the local dry bias to acceptable values (less than a few tenth of g/kg).

Much work has been devoted to improving the simulation of summer precipitation. In order to better focus on the Central Plains region, reduce the computational requirements for the proposed experiments and speed up the completion of the project, the model domain was reduced (compared to the original experiments) to cover only the central and western U.S. rather than the whole continent. Two cases, summer of 1988 and summer of 1993 were chosen to test the model simulation of summer precipitation, since they are representative of a dry and a wet regime over the Central Plains. Boundary conditions were provided by ECMWF analyses of observations. We tested different model precipitation parameterizations and performed several adjustments on the setting of key parameters.

A model configuration was found which showed a reasonably good performance in simulating various characteristics of surface climatology

over the region during these two extreme periods, with total simulated precipitation being close to observed in May, June, July (MJJ) 1988 and lower than observed by about 25 in MJJ 1993. The simulated surface hydrologic budgets and different precipitation statistics over the Upper Mississippi Basin were also analyzed in the paper, along with the model sensitivity to soil water content. This model configuration was then tested in a 2-year long simulation (fall 1986 through summer 1988) to verify the model simulation of seasonal climatology.

Results to Date: This 2-year run was recently completed, and we have preliminarily evaluated the climatology for both years (fall 86 – summer 87 and fall 87 – summer 88). The model performs best (when comparing mean seasonal temperature and precipitation with observations) in fall and winter (Figure 1). In spring, the pattern of precipitation over the central Plains is fairly well reproduced, although there is too much precipitation in the northwestern segment of the domain. Summer is still the season most difficult to simulate. The model produces too much precipitation over the Great Plains and model temperatures are too warm by about 2°C.

The other main research accomplishment at NCAR was evaluation of candidate general circulation models (GCMs) for the nested model runs over the Central Plains. Three GCMs are currently available for the nested model runs proposed in the present project: the NCAR GENESIS GCM (version 2.0), the Washington-Meehl version of the Community Climate Model (CCM) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) GCM. Output from present day and 2xCO experiments with these AGCMs coupled with mixed layer ocean models is available and has been analyzed to evaluate the model performances over the continental U.S. Based on temperature and precipitation criteria, the CSIRO model appears to perform the best over North America, although its 850 mb wind field appears a bit weak over the central U.S. From these preliminary evaluations we have tentatively chosen the CSIRO model to provide boundary conditions for the nesting experiment.

Crop Modeling Work at NCAR and Nebraska.

At NCAR two CERES crop models (soybean and winter wheat) have been set up for multi-year runs; and testing of the models at locations in

Eastern Kansas and Iowa has begun.

At Nebraska procedures were developed to examine the agreement between observed and modeled estimates of crop productivity at different levels of spatial aggregation of climate and soils data. The procedures were tested on two pilot grid cells in the Great Plains study area: eastern and western Iowa. The procedures were developed with observed climate data in preparation for their application to the testing of climate scenarios developed with the RegCM for the central Great Plains. The observed climate record (1984-1992) has been constructed for two test grid cells, whose size corresponds to a typical GCM high horizontal resolution (2.8 Lat. and Long.), superimposed on Iowa (Figure 2). The GCM-size grid cells were subdivided into 9 and then 36 sub-grid cells. EPIC model farms and cooperative observing station climate data were organized for each of the three levels of aggregation (GCM, 9 sub-grid, 36 sub-grid scales). Observed county-level annual crop yield data (1984-1992) were aggregated to those three levels for comparison with crop model simulations.

Tests were performed to examine the agreement between simulated crop yields and observed yields over the three levels of spatial aggregation. The tests involved manipulation of only the climate and soils data. In one set of manipulations, climate data first were left aggregated at the GCM scale in the form of areal averages (referred to in tabular results below as "spatially uniform") and then climate data were disaggregated to each of the two subgrid scales (9, 36, referred to in tabular results as "spatially differentiated"). Soils were handled in the same manner as the climate data, with the most abundant soil-type representing the spatially uniform class for any given grid cell. All combinations of climate and soil aggregations were examined. In all cases, tests involved measuring the agreement between modeled crop yields and observed yields at different levels of aggregation, with the test statistic being the R. The initial crop tested was dryland maize.

In the eastern Iowa grid cell, the greatest agreement between modeled and observed yields ($R = 0.67$) occurred when climate data were disaggregated to 36 subgrid cells, but using only a single soil type for the entire GCM grid cell. In western Iowa, the greatest agreement ($R = 0.80$) occurred when both climate and soils data

were disaggregated to 36 subgrid cells. The least agreement between modeled and observed yields occurred when climate and soils data were aggregated at the GCM scale. Though the best agreement between modeled and observed yields occurred at the finest grid resolution (36 subgrid cells) of climate data, the greatest improvement in agreement came in the initial disaggregation of climate data from the GCM grid cell to the 9 subgrid cells. Further disaggregation of climate data from 9 to 36 subgrid cells yielded only marginal improvement in agreement between modeled and observed yields. In virtually all cases, added spatial detail of soil types does little to improve agreement between modeled and observed yields.

Manuscripts in preparation and submitted:

Giorgi, F., L. Mearns, C. Shields, and L. Mayer. A Regional Model Study of the Importance of Local versus Remote Controls of the 1988 Drought and the 1993 Flood over the central United States, submitted to J. Climate.

Presentations:

Mearns, L.O., F. Giorgi, and C. Shields. RegCM Model Results over the Great Plains, NIGEC PI's Meeting, Lincoln, Nebraska, Sept. 24, 1994.

Easterling, W.E., C.J. Hays, L.O. Mearns, etc. Human Dimensions of Global Change Meeting, Duke, North Carolina, June 1995.

1. Fall (September, October, November) 1986 observed (a.) and modeled (b.) mean temperature (°F); and observed (c.) and modeled (d.) total precipitation (total inches). For precipitation, contours above 8 inches are shaded. Observations are from the issue of Weekly Weather and Crop Bulletin, Dec. 23, 1986.

Figure 1 continued.

Scale Resolution

☆ Locations of weather stations used in
EPIC's weather generator

● Locations of cooperative weather stations

Figure 2.

The Detection of Climate Change Using Long Term Daily Climate Records Over Grassland Regions of the Northern Hemisphere

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Objectives: The primary objective of this research project is the synthesis of a new type of climate change scenario, based on a minimal use of GCM guidance and a reliance on long term records of daily observations of the seasonal cycle to provide suitable climate analogs. The calendar shift method, as it has been named, will be utilized in the coming year to provide a variety of climate scenarios for studies of the sensitivity of the soil water budgets of the Great Plains to potential future climate states.

Secondary goals in support of the primary objective include the preparation and quality control of long times series of daily observations; the climatological analysis of seasonal cycle relationships among temperature, precipitation, snowfall and snow cover, clouds, and dew point; the generation of historical water budgets for the Great Plains region; and the examination of climate change in the Great Plains at sub-monthly temporal resolution. All of these activities are necessary to increase the understanding of the observational data being

used for climate change scenario production, correct scenarios for climatological incongruities caused by calendar shifting hydrologic variables (such as snow cover) that are affected by radiation, and complete thrusts that were initiated in the first year, prior to the establishment of the present primary objective.

Products: The calendar shift methodology for generating climate change scenarios is the primary product of this project year. The generation and analysis of several different climate scenarios (based on differing GCM guidance) for the Great Plains will be completed in late summer. During the next year, the water budget characteristics of these scenarios will be calculated to assess the range of possible climate change impacts represented by the scenarios.

Project outputs nearing completion or already completed include: 1) quality controlled daily climate records extending for over one hundred years in the Great Plains; 2) identification of the physical processes responsible for regional differences and asymmetries in daily resolution temperature seasonal cycles; 3) analysis of mechanisms responsible for coherent climate change signals of less than one month duration within the seasonal cycle; and 4) development of a climate change detection method based on seasonal fingerprint characteristics.

Approach: The basic idea of the calendar shift method of generating climate change scenarios is to use the seasonal cycle itself to provide analogs for future states. In the Great Plains, the amplitude of the seasonal cycle is large enough that a simple reassignment of daily observations to a new set of calendar days shifted towards winter can provide scenarios for all days but the central period of summer. A scenario created in this manner has the advantage of possessing dynamically consistent relationships between variables and climate processes, as any day of the scenario consists of observations taken on a single day throughout the Great Plains.

Monthly GCM temperature output for a region provides the temporal guidance for the calendar shift. Large scale temperature is one of the more reliable products of GCMs, as most models are tuned to deliver accurate surface temperature conditions in control runs. No GCM precipitation fields are used in this approach. In

addition to equilibrium $2\times\text{CO}_2$ - $1\times\text{CO}_2$ model change projections, scenarios for three periods during a transient run by the GFDL GCM are also being produced.

While the calendar shift method is based on a simple idea, there are quite a few complexities that must be overcome. Methods for repairing discontinuities where adjacent shifted months overlap or gap, adjusting snow cover for the radiation input differences when shifting within the season, and filling the summer gap induced by shifting days toward winter have all been addressed. The summer temperature gap is filled with daily data that are not calendar shifted, but are instead temperature shifted by the magnitude of the GCM $2\times\text{CO}_2$ - $1\times\text{CO}_2$ model projection differences. An additional temperature shift is made to the early and late summer periods near the summer gap, in order to remove a step change at the transition. No adjustment is made to precipitation amounts or variability, as there are considerable disagreements regarding Great Plains precipitation projections between various GCMs.

The impact of various climate scenarios on hydrologic parameters in the Great Plains will be assessed in the coming year using the Thornthwaite-Mather climatic water budget methodology. A simple approach is made necessary by the present limitation of the scenario generation to temperature and precipitation variables. However, this water budget approach has been demonstrated to be quite robust for a great variety of circumstances. Inputs also include date and latitude for solar calculations; the dates will be set by the calendar shift, thus explicitly making a radiation adjustment to the water budget calculations. The water budget values for the last 100 years have also been calculated for comparative purposes.

Methodologies for the secondary goals consist of univariate and multivariate statistical analyses. Our focus on daily resolution data from long observational time series provides us with a unique perspective that is allowing us to address some fundamental aspects of climate processes. Climatological relationships between daily resolution seasonal cycles of temperature across space have been identified with regression and principal component analysis. The identification of trend annual cycles, constructed from the trends of individual day temperature time series, is another unique method developed for this

project. This has been utilized both for climate change detection and the assessment of climate change processes.

Results to Date: In this section, the discussion is confined to results from Year 2. The main objective of Year 2 has been achieved: the development of the calendar shift methodology for climate change scenario generation. A calendar shifted scenario for Gothenberg, Nebraska is shown in Figure 1. The $2\times\text{CO}_2$ - $1\times\text{CO}_2$ temperature change in the central and northern Great Plains in the Canadian Climate Center (CCC) GCM were spatially averaged for every month. The differences between the model runs range from 3.71°C in November to 9.06°C in February. Setting the nadir of winter at January 14, each half of the year is calendar shifted, so that warmer, more summer-like days are taken to represent dates closer to winter. Because of the enormous warming generated in the CCC model, the period from June 22 to August 22 does not have a seasonal analog. This is a worse case; the gap is narrower in scenarios utilizing a GFDL GCM simulation of transiently increasing CO_2 levels. The gap period, as mentioned above, is shifted to warmer temperatures without any change in the representative calendar day.

The second part of Figure 1 shows a comparison between the CCC GCM $2\times\text{CO}_2$ output for a grid point near Gothenberg with the calendar shifted change scenario. The agreement is substantial, except for the spring, where the model starts out with temperatures in its control run that are colder than observed. The calendar shifted scenario, while representing a temperature change similar to model, provides tremendous advantages. First, all the scenarios produced in this study have 50 year or more of data, including all the natural variability of the real climate system. Second, the same calendar dates can be used to provide scenarios of other variables such as precipitation. Finally, all the scenario variables will be dynamically consistent, having been drawn from the same real daily observation set.

In preparation for the impact analysis, a 100-year climatology of water budget variables for the Great Plains region of the United States has been completed. This new data base will allow us to better understand changes in hydrologic parameters such as soil moisture under temperature and precipitation regimes generated

by our calendar shift methodology. Figure 2 shows the average growing season (April through September) soil moisture deficit across the Great Plains region for the period 1895 through 1994. As is well known, the plains region lacks sufficient water input during these months for the growth of several crop species without the benefit of irrigation. However, the variability around this mean is quite large, and is captured by this data set. During the growing season of 1936, for example, deficit values across the plains region were greater than 10 inches over the entire area. Alternately, during the growing season of 1993, much of the plains region experienced no soil moisture deficit. Instead, surpluses of soil moisture of over 10 inches were found across eastern sections of the region. This data base will be invaluable for comparisons with our water budget scenarios.

Our examination of the annual cycle of the daily temperature range and the mechanisms that control it is nearing completion. Our work has shown that there are distinct regional differences in the annual cycle of the daily temperature range across the coterminous United States. These annual cycle differences are attributed to two major synoptic controls: the annual cycles of both dew point temperature and cloud cover. For example, across the northern High Plains of the United States the daily temperature range is strongly associated with the annual cycle of cloud cover. The average annual cycles of both variables at Billings shows that the peak in daily temperature range in August is simultaneous with a minimum in the average daily cloud cover (Figure 3). However, the cloud cover/temperature range relationship does not hold for other sections of the Great Plains. In many of these areas, the annual cycle of the dew point temperature is strongly associated with the daily temperature range.

The assembly of a snow data base for further comparative analysis with other variables has been completed. This set includes daily reports of snow cover and snowfall from either first-order or cooperative stations located near the sites where we have full dew point and cloud coverage data. These data are from the Historical Daily Climate Dataset (HDCLD) developed by Robinson, and have already been subject to a first-order quality control. A more detailed assessment of data from candidate stations will also be undertaken in the final selection process. As a result, the stations ultimately selected should

have few if any instances of missing or questionable data. Mean daily climatologies are being created for such conditions as days with greater than or equal to 1", 3", 6".... of snow cover, and for days exceeding certain snowfall thresholds. These data will also be utilized in creating snow adjustments for climate change scenarios to account for the effects of radiation input changes due to calendar shifts.

Many other results are in the process of final analysis and/or paper preparation, and were discussed in the Year 1 progress report. Please refer to this document for further information.

Presentations:

Robinson, D.A., D.J. Leathers, M.A. Palecki, and K.F. Dewey 1993: Climate variability as seen in daily temperature structure. MINIMAX Workshop, College Park, MD, September 27-30, 1993. Sponsored jointly by the National Oceanic and Atmospheric Administration National Environmental Watch Program and the Department of Energy Global Change Research Program.

Palecki, M.A., 1994a: The Onset of Spring in the Eastern United States During the 20th Century. Sixth Conference on Climate Variations, American Meteorological Society, Nashville, TN, January 23-28, 1994.

Palecki, M.A.: Detection of climate change through the use of daily resolution observations. Nineteenth Climate Diagnostics Workshop, College Park, MD, November 14-18, 1994.

Climate Variability and Change in the Instrumental Record: Daily Time Periods, Annual Meeting of the Association of American Geographers, San Francisco, CA, March 29 - April 2, 1994
(A conference special session organized by M.A. Palecki):

Robinson, D.A., 1994: Issues concerning the quality of daily climatic data.

Dewey, K.F., 1994: Spatial and temporal singularities in a long-term daily max/min temperature series.

Palecki, M.A., 1994b: Sub-monthly scale climate dynamics.

Proceedings:

Robinson, D.A., D.J. Leathers, M.A. Palecki, and K.F. Dewey 1993: Climate variability as seen in daily temperature structure. Pages 201-230 in: Asymmetric Change of Daily Temperature Range - Proceedings of the International MINIMAX Workshop, College Park, MD, September 27-30, 1993. Department of Energy.

Palecki, M.A., 1994: The Onset of Spring in the Eastern United States During the 20th Century. Pages 108-109 in: Pre-Print Volume, Sixth Conference on Climate Variations, American Meteorological Society, Nashville, TN, January 23-28, 1994.

Palecki, M.A.: Detection of climate change through the use of daily resolution observations. Pages 277-280 in: Proceedings of the Nineteenth Climate Diagnostics Workshop, College Park, MD, November 14-18, 1994.

Journal Article:

Robinson, D.A., D.J. Leathers, M.A. Palecki, and K.F. Dewey. Some observations on climate variability as seen in daily temperature structure. Atmospheric Research (in press).

Articles and Papers in Preparation:

Leathers, D.J., D.A. Robinson, M.A. Palecki, and K.F. Dewey: The spatial structure and a synoptic climatology of the annual cycle of daily temperature range over the United States. To be submitted to International Journal of Climatology.

Dewey, K.F., M.A. Palecki, D.A. Robinson, and D.J. Leathers: A climatology of asymmetries and singularities in the annual cycles of max and min temperatures for the conterminous United States. To be submitted to International Journal of Climatology.

Palecki, M.A., K.F. Dewey, D.J. Leathers, and D.A. Robinson: Fine temporal structures in seasonal climate change. To be submitted to Journal of Climate.

Student Participation: Natalie Williams 50%

Figure 1.

Figure 3. Billings, Montana.

Figure 2. Average growing season soil moisture deficit.

Natural Responses of Shallow Lakes and Wetlands for Measuring and Analyzing Impacts of Climatic/Environmental Change

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Objectives: 1) Perform historical analyses of hydrological, biological, and climatological signals and fluxes relating to selected lake/wetland systems in the Nebraska Sand Hills to establish base-line conditions against which "environmental variance" can be assessed; 2) evaluate the relationships between/among hydrological, biological, and climatological signals and fluxes as they relate to lake/wetland processes in order to facilitate the modeling of environmental conditions, given selected climate scenarios; 3) investigate the variability over time in the flows of energy and carbon production; and 4) measure and map the spatial distributions of conditions related to the natural production of trace gases.

Products: A final project report, symposium presentations, papers published in peer-reviewed journals, and an assortment of maps and graphs of selected parameters measured over time (available to interested parties upon request).

Approach: The approaches vary per objective, but are oriented primarily to analyses of available historical climatological and groundwater-level data, and on image analysis of remotely acquired data from (principally) the Landsat Multispectral Scanner (MSS), the Landsat Thematic Mapper (TM), and the European Space Agency's ERS-1/-2 synthetic-aperture radar instrument. Some attention is also being given to the recording of field data at selected sites; e.g., lake elevation, water temperature, spectral reflectance, and vegetative biomass.

Results to Date:

Developing Relationships Between Hydrological and Climatological Signals and Fluxes To recognize long-term impact(s) of potential environmental change on Sand-Hills lake/wetland systems, it is necessary to develop hydrological, biological and climatological databases, on

various time scales. We have obtained and analyzed historical data on lake-surface areas (from satellite images), lake elevations, groundwater elevations, precipitation, and selected climatic parameters for the two primary study sites, the Crescent Lake (CLNWR) and Valentine National Wildlife Refuges (VNWR). Because of the superior spatial and temporal density of data at the former location, however, most of our work to date is focused there.

Preliminary findings confirm the suggestion of Rundquist et al. (1987) that fundamental relationships exist among the timing and amounts of precipitation, fluctuations in groundwater levels, and both the pool elevations and surface areas of individual lakes. We will continue to refine and develop subtle details of such connections for various lakes in the primary study sites, but the establishment of these linkages allows remote monitoring of hydrologic conditions for hundreds of Sand-Hills lakes lacking groundwater-recording instrumentation.

Forty-two Landsat-MSS scenes covering the Western Sand Hills have been georeferenced and processed to correct for changing solar-illumination angles. Figure 1 summarizes the total lake-surface area for the 130 study lakes (combined) for each of the 42 images. The dashed line (A on graphic) represents the average total surface area for the 42 dates. Although a comparison with daily climatic data will not be completed until remaining scenes have been processed, some interesting points can be noted. For example, the image date of August 4, 1980 (B) is the lowest total lake-surface area found to date. Examination of climatic data from the nearby Oshkosh and Dalton stations reveals that the precipitation from March 1, 1980 to August 4, 1980, was approximately 4 inches below normal. In contrast, the May 7, 1987 scene (C) was

acquired after 3.96 inches of precipitation (over a four-day period) occurred at the CLNWR. This latter scene contains the maximum amount of lake-surface area to found to date.

Additional patterns can be seen in Figure 1, especially for 1981 and 1983, when numerous good Landsat-MSS scenes were available to us. Both years show a brief increase in lake-surface area during the early portion of the growing season, followed by a decrease in surface area, and ending in October with a slight increase in surface area. The region is characterized by a precipitation maximum in late Spring/early Summer, which is indicated by the early maximum lake-surface area shown in Figure 1. Evapotranspiration for the region tends to increase during the Summer months with a definite decrease in precipitation, a tendency also supported by the surface-area-estimation curve. The slight rebound in lake area during October could be caused by a combination of increasing precipitation and, more importantly, decreasing evapotranspiration. The latter would allow for precipitation and inflow from below-ground sources to recharge the lakes.

Figure 2 allows comparison of the total surface area of the 130 lakes selected for study and all standing water (including "ephemeral ponding") in the entire study area. The trends of the two curves are similar, with minor exceptions, due probably to the fact that the lakes tend to be better connected to underground water, while the ephemeral ponds are obviously not.

We have begun interpretive modeling to gain insight into the controlling parameters affecting the seasonality of groundwater-flow patterns around the Roundup-Island Lake System, at the CLNWR. In support of this activity, we installed instrumentation to obtain high-density temporal and spatial data along a transect from Roundup to Island Lake. Data include groundwater elevation, relative humidity, ambient air temperature, and precipitation (e.g., see Figure 3). Sampling rates have varied from one-half to every four hours, and results are quite instructive.

The model that we are applying is the recent modification of the widely used USGS groundwater flow model, "MODFLOW," by Cheng and Anderson (1993) to include fluctuating lake-surface water levels. The performance of the MODFLOW lake package has been verified.

Changes in lake area, documented using Landsat-MSS images, are due to variations in the input and output components of the water balance of the lake. Therefore, we have developed a finite-element-model grid to correspond with the Landsat-MSS image resolution of 79 by 79 meters. Our current modeling efforts are focusing on the seasonal dynamics of groundwater flow in the Roundup-Island Lake system as a function of changes in the water balance.

Wetland Vegetation A second area of our research includes using well-established remote-sensing and digital-processing techniques to analyze both current and archived data acquired over the wetland vegetation at our study sites. Specifically, for the CLNWR site, we have determined that individual wetland species cannot be identified using the current 80- and 30-meter spatial resolutions of the MSS and TM, even though our field-spectroradiometer data for individual species indicate potential for spectral separability. Therefore, we are currently attempting to digitally classify and measure the spatial extents of wetland communities in the Sand Hills, rather than species. We have detected and mapped changes in vegetative greenness of communities at various times from 1972 to the present, as previously reported. We are also currently attempting to calibrate satellite measures of above-ground biomass of wetland vegetation with in-situ measures. Our goal is not only to relate these parameters to hydrological and climatological data but also to link findings to the on-going trace-gas research of other NIGEC investigators.

In addition, we are beginning to develop methods for incorporating long-wavelength, orbital radar into analyses of optical data. Preliminary results indicate that C- and L-band radar are sensitive to changes caused by the growth and flowering of emergent wetland species. Surprisingly, we have also learned that detection of submergent communities in shallow lakes seems possible with C-band data. Additional goals are to use orbital radar to document the presence/absence of standing water beneath fully developed wetland canopies, and to monitor soil-moisture patterns around lake systems (as well as enhance digital classifications of wetland vegetation).

Students Participating in Various Aspects of this Project (*=NIGEC funding): Rod Fraser

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Figure 1. Combined surface areas for 130 study lakes, per image date.

Figure 2. Comparison of combined surface areas for 130 study lakes and all water standing in study area, per image date.

Figure 3. Example of in-situ data collected in the Roundup/Island Lake transect.

Assessment of Climate and Management Induced Directional Changes in Great Plains Vegetation with NDVI and Stable Carbon Isotopes

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Objectives: The carbon isotopic signature, $\delta^{13}\text{C}$ value, quantitatively characterizes the two main photosynthetic systems, C_3 and C_4 , in the Great Plains. The ability of stable isotopes of carbon to integrate ecosystem processes, to quantify carbon fluxes from the atmosphere by temperature sensitive photosynthetic types, and to provide isotopic labels which preserve historic and prehistoric carbon sources allows us to examine the response of Great Plains systems to climate change, to management induced directional change in vegetation, and to other human induced perturbations. C_3 and C_4 species have different temperature requirements, and their proportions in the floras at any specific latitude vary in response to temperature and, perhaps, other climate and biogeographic factors.

Our main objective is to determine if today's native grassland systems are in a long-term steady state with climate or the degree to which they depart and the direction in which change is proceeding. We intend to integrate soil fractionation techniques with ecosystem modeling approaches to assess the fluxes of carbon from various SOM fractions, the turnover of these fractions under steady state natural and managed agricultural systems, and the potential for land remediation and the sequestering of carbon. A second objective will establish biophysical attributes to NDVI or other vegetation indices in grasslands and to assess yearly uptake of carbon by the dominant C_3 and C_4 systems in grasslands. A third objective will describe the effects of land management on SOM stability, turnover, and carbon flux. We intend to develop a predictive capability to describe community change, movements of land cover classes, and changes in net carbon flux by each photosynthetic type in response to long-term climate change.

Products: We will describe the land cover classification of grassland types in the Great

Plains and interpret the performance of these classes from remotely sensed data. Analyses of these classes and their performances will be assessed with time series of AVHRR-derived reflectance data supplemented with potential production and species composition estimated from the STATSGO data base and field isotopic analyses of selected native prairies across North America. We will secure a fairly dense climate record and provide a prediction of factors controlling the proportional contribution of C_3 and C_4 species to primary production. Land cover classes and their performances across the Great Plains will be interpreted based on this contribution. We intend to describe modern distributions of production by species or photosynthetic types. We will derive the seasonality of production by type and begin to develop estimates of annual carbon uptake by land cover class and photosynthetic type.

In addition to the isotopic analysis across the Great Plains, we will focus on an understanding of the dynamics of SOM changes as a function of land use. We will provide detailed descriptions of SOM changes in native prairie and agriculturally managed systems. This will be based on stable isotopic composition as well as fairly frequent ^{14}C dating of various SOM fractions from several systems. We intend to quantify the rates at which carbon in SOM of various soil fractions turns over, and we will incorporate this understanding in an implementation of a modified version of CENTURY which will incorporate greater depth dynamics and isotopic balances.

Approach: Our research incorporates several seemingly diverse approaches to the study of Great Plains climate change. Stable isotopes of carbon are used to quantify fluxes from various pools of carbon, mainly atmosphere, plant, and SOM, and to allow us to interpret successional changes in vegetation as well as steady state

relationships between SOM isotopes and climate. This requires the analytical capabilities of an isotope ratio mass spectrometer and the SOM fractionation techniques worked out with Cambardella. Remote sensing, mainly AVHRR data, allow us to monitor grassland land cover classes across the Great Plains and at specific sites where biomass and biophysical relationships can be derived. Ultimately we believe this will allow us to calculate production and net carbon flux across what we define as ecosystem performance types. The integration of our understanding across both time and space is facilitated by modeling of SOM dynamics from our site specific data where we can quantify changes associated with land use as well as place prairie sites in a longer term Holocene perspective.

Soil samples have been obtained from 75 native prairie sites across North America with four to six replicate pooled soil samples stratified by depth. These have been analyzed for bulk stable isotopes following preparation and are still in the process of being carbon dated. Several matched land use systems near Rockefeller Prairie in Kansas and in North Dakota have been examined in detail with particle-size and density fractionation of SOM. The STATSGO data base serves as a source of production estimates as well as contributions by the main species, which we determine for photosynthetic type. These data are aggregated in a GIS system and intersected with climate data and AVHRR-derived land cover classes for further analysis. This analysis includes a detailed set of metric features, e.g., onset period, maximum period, time integrated NDVI, etc. which we can interpret in light of our isotopic estimates of contribution by photosynthetic types. AVHRR data and analyses are performed at the EROS Data Center. Modeling of SOM dynamics is done with a STELLA version of CENTURY to facilitate the isotopic changes which we wish to simulate.

Results to Date:

Land Cover Analysis: The integration of our field isotopic work, land cover classification, and the STATSGO data base has allowed us to interpret the performance of major grassland land cover classes in the Great Plains. Table 1 summarizes the areal extents and major grass components in these classes and our estimate of percent contribution to production by each photosynthetic type. Note that the contribution by C_4 species

varies from 94% in the south to a low of 29% in the north. The classes possess distinct patterns of NDVI with a consistent relative performance across five years of quite variable weather. Production seems largely independent of composition by photosynthetic type but clearly documents an east to west decrease in time integrated NDVI, with, however, a large increase in the time integrated value during 1993 with the high precipitation which reduced NDVI in agricultural classes to the east. The most notable feature is an early onset in land cover classes to the north, classes which are dominated by C_3 species. Apparently, these types are largely excluded in areas south of Nebraska, resulting in a late onset of greenness as C_4 species initiate growth. Variability within classes, relationships with photosynthetic types, and climatic controls over metric features need to be determined.

Climate and Prairie Composition: Both the isotopic data and analysis of STATSGO data have been used to determine the control over contributions to production (as distinct from floristic composition). Isotopic data suggest that the soil is not in steady state with the atmosphere in part because of the anthropogenic signal which is working its way through the profile and into recalcitrant fractions. Many sites, however, also suggest a greater contribution by C_3 species than can be accounted for by the anthropogenic correction. More important, however, both STATSGO and the isotope data show that similar environmental variables are important in determining proportional contribution to production. Table 2 summarizes some data for the surface (A) horizon as well as the horizon which is generally the most positive (usually at a depth around 15 cm). In most analyses proportional contribution by C_4 species is related positively to high temperature during the growing season and precipitation in July and negatively to the low temperature in April. Often sand is significant but only in a minor way. These isotopic and STATSGO data suggest that C_4 production is favored by both high temperatures during the growing season and late growing season precipitation. High temperature during early spring, however, may favor C_3 species. These relationships are quite different than those produced some time ago based on floristic composition. Comparisons of prairie relicts and adjacent forests on the Loess Hills (e.g., Newton Hills, S.D.) also document that successional changes from prairies to forests have occurred

and are continuing today. Detailed analyses at Rockefeller prairie show that seemingly intact prairie systems are being shifted to forbs, as shown isotopically, apparently because of management.

Land Use and SOM: We have completed the soil fractionation and stable isotopic analyses of soil cores through the profile (to 100 cm) from control prairie, various land use, and various CRP type systems in our test site in Kansas. Figure 1 summarizes much of this isotopic information and clearly shows a good mass balance, the large turnover of carbon associated with agriculture but that this turnover is a function of depth in the profile as well as SOM fraction. SOM in coarse clay particles are the most recalcitrant and turnover decreases with depth in the profile. Most of the ^{14}C dating has now been done and mean residence times confirm our interpretations based on stable isotopes and should allow us to derive good estimates of rates of turnover. We have also begun to interpret the dynamics of this turnover. Lignin, believed to be responsible for recalcitrant SOM, changes in isotopic composition during mineralization. But, importantly, its isotopic value approaches that of the SOM in which it is decomposing. This suggests that the basic lignin structure is being remodeled, perhaps by action of microbes on exposed functional groups of these complex molecules.

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Other products: Land cover classification and related AVHRR and grassland composition data are available in digital form.

Student participation: Donovan DeJong 75%; Joel Vander Kooi; 20%; Jon Outland 25%; Chris Skaar 25%; Gretchen Green 10%; Nathan Skalsky 25%; Scott Moeller 10%.

Table 2. Multiple regression analysis of the effect of climate and soil variables on the proportional contribution of species to the production of native prairie sites across the Great Plains of North America. Input data in the analysis include isotopic information from approximately 75 native prairie sites and biweekly climate data gridded across the Great Plains. Variable included are those which were generally statistically significant in analyses of isotopic and STATSGO data with climate or soil variables.

A horizon

Variable	Coefficient	p value
Intercept	-39.179	<.0001
Low Temp for April	-.021	.8638
Precipitation for July	.718	<.0001
High Temperature for Growing Season	.643	<.0001
%Sand	-.001	.8886

Positive Horizon

Variable	Coefficient	p value
Intercept	-39.701	<.0001
Low Temp for April	-.080	.5389
Precipitation for July	.840	<.0001
High Temperature for Growing Season	.685	<.0001
%Sand	-.011	.1770

Table 1. Seasonal land cover classes from the Great Plains, labels and areal extents, and C₄ composition expressed as the potential contribution to production during normal years derived from the STATSGO data base.

Class	Label	km ² /Class	C ₄ Grass	Percent Total
65	Bluestem, Indiangrass, Switchgrass	46701	79	70
35	Bluestem, Grama, Wheatgrass, Small Grains	78304	72	63
59	Wheatgrass, Blue Grama, Needleandthread	107011	51	44
61	Wheatgrass, Blue Grama, Needleandthread, Big Sage	124024	39	34
56	Wheatgrass, Needlegrass, Needleandthread	115682	29	26
64	Wheatgrass, Needlegrass, Needleandthread	58920	45	39
75	Greasewood, Sage, Wheatgrass, Needleandthread	30641	37	32
80	Blue Grama, Buffalograss, Big Sage, Saltbush	78243	80	71
57	Bluestem, Blue Grama	13298	79	73
58	Blue Grama Wheatgrass, Buffalograss	14066	84	73
76	sand Sage, Blue Grama, Wheatgrass, Buffalograss	37678	97	83
81	Sand Sage, Oak, Blue Grama, Buffalograss	48085	94	82
86	Bluestem, Sand Sage, Blue Grama, Oak, Juniper	56103	94	83

Figure 1. Stable isotopic composition (means of 4 replicates, S.E. smaller than the symbol) as a function of depth through the profile and particle size/density fractions. Categories are light fractions that pass through mesh sizes of 500, 250, 53 microns and a heavier component "X" from these light fractions and the heavy fractions of coarse silt =CS, fine silt =FS, coarse clay =CC, and fine clay =FC. Note the departures of individual fractions from the bulk soil by the dashed lines, indicating that the systems are not in steady state. KUC = Rockefeller Prairie Control, CRP = conservation reserve program analogue, B = long term brome after agriculture, AG = normal agricultural practice since prairie was broken.

An Integrated Investigation of Carbon Dioxide and Methane Fluxes in Mid-Latitude Prairie Wetlands: Micrometeorological Measurements, Process-Level Studies and Modeling

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Objectives: Our overall objective is to expand the currently limited body of knowledge on surface fluxes of carbon dioxide and methane in mid-latitude prairie wetlands. Consequently, we are measuring surface fluxes of carbon dioxide, methane and energy, and a suite of physical, chemical and biological variables. Process-level studies, designed to quantify factors regulating methane emission, are also being conducted.

Products: We will produce a unique data set on fluxes of carbon dioxide and methane in these relatively unstudied mid-latitude prairie wetlands. Concurrent micrometeorological and chamber flux measurements will allow temporal and spatial variation in fluxes of carbon dioxide and methane to be related to underlying biological and biophysical processes. Process-level models of methane fluxes will be improved and tested.

Approach: During 1993 we investigated 18 potential sites in the Sandhills region of Nebraska and selected Ballards Marsh near Valentine, NE as our study site for detailed, intensive measurements of fluxes of carbon dioxide, methane and energy. The Ballards Marsh site provides an excellent upwind fetch for the micrometeorological measurements and is characterized by three well-defined plant community types. The first is dominated by 2-3 m tall common reed grass (*Phragmites australis*). The second is dominated by 1-2 m tall bulrush (*Scirpus acutus*). The third main community occurs in areas of deeper, open water, where wild rice (*Zizania aquatica*) is the major emergent species and a submergent pondweed (*Potamogeton*) species is very common. Flux measurements at wetland sites require extensive infrastructure (e.g., boardwalks, instrument platforms for micrometeorological

instrumentation, platforms for sampling surface carbon dioxide and methane fluxes using chambers). These were installed in 1993 and described in previous progress reports.

Results to Date:

1) Micrometeorological flux measurements:

In 1994, we completed the installation and check-out of eddy correlation and other micrometeorological instrumentation by mid-April. Data collection began on April 19 and continued until October 14. Processing of the data continues at this writing. Some preliminary results, based on real-time raw observations, are included below.

a) Components of surface energy balance: Typical diel courses of energy balance components on a clear day in a *Phragmites*-dominated site are shown in Fig. 1. The heat stored in the water and sediment layer (W) was about 30% of net radiation (Rn). During midday, 50% of Rn was partitioned to water vapor flux (LE) and 20% of Rn to sensible heat flux (H). Energy partitioning changed with the development of the vegetation canopy and its senescence, and with the fluctuations in water table elevation. We observed several occurrences of advection of sensible heat, which resulted in enhanced evapotranspiration. In the spring of 1994, we installed instruments to measure the surface energy balance at two other locations (*Scirpus*-dominated and open water) at the Ballards Marsh study site. Details of the diel and seasonal characteristics of energy partitioning in these three main plant community types (i.e., *Phragmites*, *Scirpus*, open water) are being investigated.

b) Net ecosystem carbon dioxide exchange: We began CO₂ flux measurements on April 19 just before the plants started emerging above the water surface. Until the vegetation reached a canopy height of 0.2-0.5 m (above the water surface) and developed one or two small green leaves in mid-May, the marsh was a net source of atmospheric CO₂, releasing CO₂ at rates of 0.05-0.1 mg m⁻² s⁻¹ throughout the day. In late May, the marsh quickly changed from a source to sink for CO₂. The net uptake of CO₂ during daytime increased rapidly from 0.2 mg m⁻² s⁻¹ in late May to 0.8 mg m⁻² s⁻¹ in August. Typical diel variations in CO₂ flux during the peak growth stage (late July) are shown in Fig. 2. The CO₂ flux reached a peak during mid- to late-morning hours. At night, the measured CO₂ flux indicated a release of CO₂ into the atmosphere at rates of about 0.1 mg m⁻² s⁻¹. In September, magnitudes of both daytime and nighttime CO₂ fluxes decreased rapidly as the vegetation senesced, and the CO₂ exchange between the marsh and the atmosphere approached zero in October.

c) Net methane emission: During the early part of the season (late April-late May) midday methane flux ranged from 100 to 200 mg m⁻² d⁻¹. During the period from early June to early July, the methane flux increased from 250 to 600 mg m⁻² d⁻¹. Midday methane flux reached a peak during August-early September and varied from 600 to 1200 mg m⁻² d⁻¹. Toward the end of the season (mid September-mid October), with senescing vegetation and falling temperatures, methane flux decreased to small values (100-350 mg m⁻² d⁻¹). Significant diel variation, as found in the 1993 season, was repeatedly observed throughout the 1994 season. Typical diel patterns in methane flux are shown on two consecutive days in late July, 1994 (Fig. 3). Methane flux usually reached a peak during mid to late morning hours. During the stage of peak growth (July-August), daytime CH₄ flux typically ranged from 300 to 1000 mg m⁻² d⁻¹. Nighttime flux, however, remained relatively constant (~250-350 mg m⁻² d⁻¹). Nighttime methane emission averaged on a daily basis also showed distinct seasonal variation and seemed to correlate strongly with changes in sediment/water temperature.

2) Chamber measurement of surface carbon dioxide flux:

Surface fluxes were measured using a chamber from May to October, 1994 at the Ballards Marsh

site at platform locations along two transects approximately 200 m east and west of the main boardwalk (leading to the eddy correlation tower). Platforms were located in *Phragmites*- and *Scirpus*-dominated vegetation communities. Surface CO₂ fluxes were small early in the season and reached a peak in the middle of August after which they declined. These fluxes appear to be correlated with canopy foliage area index and water column temperatures. Surface CO₂ fluxes in *Phragmites* communities ranged from 0.03 mg m⁻² s⁻¹ in mid-May to 0.13 mg m⁻² s⁻¹ in mid-August. Surface fluxes in *Scirpus* communities ranged from 0.03 mg m⁻² s⁻¹ in early May to 0.09 mg m⁻² s⁻¹ in mid-August.

3) Chamber measurement of individual leaf gas exchange:

We quantified single leaf gas exchange properties in detail for *Phragmites australis* and *Scirpus acutus*. Selected gas exchange measurements were also made on *Typha latifolia*. Measurements were initiated on small leaves in May and continued into early October. Some preliminary results are discussed below. The response of net CO₂ assimilation to incident light intensity was determined throughout the growing season for *Phragmites* and *Scirpus*. Assimilation rates for *Phragmites* under full sunlight were approximately 15 μmol m⁻² s⁻¹ in mid-June and reached 20 μmol m⁻² s⁻¹ by mid-July (Note: 1 μmol CO₂ m⁻² s⁻¹ = 0.044 mg CO₂ m⁻² s⁻¹). These rates decreased to around 12 μmol m⁻² s⁻¹ by mid-September. Light saturation was not always evidenced in *Phragmites*; assimilation rates tended to increase up to full light intensities (photosynthetically active radiation, Q_p = 2000 μmol m⁻² s⁻¹). Stomatal conductances under full sunlight were 0.4 mol m⁻² s⁻¹ for the mid-July period. In general, assimilation rates and stomatal conductances were smaller in *Scirpus* with net assimilation peaking in mid-July with rates near 15 μmol m⁻² s⁻¹ and stomatal conductance for the same period near 0.3 mol m⁻² s⁻¹. *Scirpus* also exhibited a higher degree of light saturation than *Phragmites*, with saturation at 1000 - 1200 μmol m⁻² s⁻¹. Under full sunlight in July, *Typha* had net assimilation rates of 22 μmol m⁻² s⁻¹ and stomatal conductances of 0.5 mol m⁻² s⁻¹. The responses of net assimilation rate to internal CO₂ concentration (C_i) in all three species were fairly typical for C₃ species. Initial slopes (carboxylation efficiencies) and C_i at ambient CO₂ concentrations were highly dependent upon

incident light intensity. The response of dark respiration to leaf temperature was determined for *Phragmites* and *Scirpus*. Respiration rates at 25 C were $1.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ in *Phragmites* and $0.7 \mu\text{mol m}^{-2} \text{s}^{-1}$ in *Scirpus*. In general, respiration rates were higher in *Phragmites* than in *Scirpus*.

4) Chamber measurement of carbon dioxide and methane flux and experimental manipulation studies:

During April, 1994, we established sixteen plots (each 4m^2) along transects to the east and west of the micrometeorological tower complex. Four of these were dominated by *Scirpus*, the other twelve by *Phragmites*. Of the *Phragmites* plots, three were used as experimental controls, three more as disturbance controls (associated with establishment of limno-corrals) and the last six were used for experimental manipulations. The nine limno-corrals were established by fencing in the plot using a doubled-over polyethylene tarp to decrease mixing of water within the plot with that outside the plot in order to retain treatments. In order to assess the impact of carbon substrate quantity and quality on CH_4 production and emission rates, we added carbon (as wheat straw) alone or in combination with nitrogen (as urea). The experimental manipulation design had a modified latin square design in which each treatment combination was paired with every other treatment combination at one of the six *Phragmites* platforms, giving three replicates of each treatment. All plots were accessed from elevated platforms in order to minimize disturbance.

We developed a new, temperature-controlled chamber system to enable whole-system measurements of CH_4 and CO_2 flux in the 4 m^2 experimental plots with minimal disturbance. These consisted of a 3 m tall x 1 m^2 transparent teflon "tent" (FEP) supported by a central mast and three PVC hoops to maintain the chamber shape. In conjunction with these whole-system chamber measurements of CH_4 and CO_2 flux, we measured open-water emissions using floating 20 L opaque white polyethylene chambers. Ebullition was measured using 24-hr accumulations in inverted, 20 cm diameter polyethylene funnels. We also measured temperatures and porewater CH_4 and CO_2 concentration profiles using permanently installed probes which had thermocouples and 2 mm diameter FEP teflon ports at several depths.

Although rates of CH_4 emission and CO_2 uptake, as assessed by the whole-system chamber, were highly variable among plots, some important patterns emerged. The control plots (no corral) had significantly higher ($p < .05$) CH_4 emissions than any of the corralled plots, but no differences were apparent in CO_2 uptake rates. These differences may be attributable to disturbance associated with the corrals and investigator traffic. Experimental carbon and nitrogen (+C+N) additions increased CH_4 emissions slightly, while carbon alone (+C) apparently decreased CH_4 emissions. We are presently analyzing the surface-water CH_4 and CO_2 concentration data to estimate diffusive fluxes using the Stagnant Film Model. Ebullitive fluxes comprised about 10-20% of the total CH_4 flux, although these were more variable than the whole-system chamber fluxes. The +C and +C+N plots had 2-3 times as high rates of CH_4 and CO_2 losses via bubbles as did the remaining plots ($p < .05$). The collectors were located below the floating mat on the +C and +C+N plots, so the bubbles should have come from the sediments. This implies that the carbon additions also affected below-ground processes. Seasonally averaged porewater gas concentration profiles indicated that CH_4 and CO_2 production rates peaked 20-30 cm below the sediment water interface. The CH_4 concentrations peaked about 10 cm higher in the profile with +C or +C+N additions, which may explain some of the apparent differences in ebullitive loss rates.

Training of Graduate Students on this Project:

Burba, Georgiy G. Surface energy balance in a mid-latitude prairie wetland. M.S. Thesis (research in progress). University of Nebraska-Lincoln. 100% on this project. \$10,350 per year (graduate research assistantship).

Vanyarkho, Olga. Responses of leaf and canopy gas exchange to environmental factors. M.S. Thesis (research in progress). University of Nebraska-Lincoln. 100% on this project. \$10,350 per year (graduate research assistantship).

Presentations:

Vanyarkho, O. and T. J. Arkebauer. Responses of *Phragmites australis* and *Scirpus acutus* leaf and canopy gas exchange to environmental conditions. Ecological Society of America 80th

Annual Meeting, Snowbird, Utah, July 31-August 1, 1995.

Valentine, D.W., W.M. Pulliam, E.A. Holland, and D.S. Schimel. An experimental manipulation of

methane emissions in a mid-latitude prairie wetland. Ecological Society of America 80th Annual Meeting, Snowbird, Utah, July 31-August 1, 1995.

Figure 1. Components of surface energy balance: net radiation (Rn), heat storage in water-sediment layer (W), sensible heat flux (H) and water vapor flux (LE).

Figure 2. Diel patterns of carbon dioxide flux and photosynthetically active radiation (Qp) in late July 1994.

Figure 3. Diel patterns of methane flux late July 1994.

Midwestern Regional Center

J.C. Randolph, Director

The geographic area of the Midwestern Regional Center includes the states of Ohio, Indiana, Michigan, Illinois, and Wisconsin. Although relatively small in areal extent, the midwestern Great Lakes states have a large population base and a large number of research universities. This area also is rich in natural resources, including the Great Lakes themselves, and significant amounts of forests and agriculture.

The Midwestern Regional Center conducts a program of research that supports important elements of the larger DOE mission for global change research. The DOE research priorities currently include: (1) examination of the consequences of global climatic and atmospheric change on natural and/or human-influenced systems, (2) investigations of the radiative forcing effect of greenhouse gases, aerosols, and clouds on the Earth's climate system, (3) quantification of the role of the terrestrial biosphere as a source or sink of energy-related greenhouse gases, particularly CO₂, and identification of the major processes and factors controlling the carbon exchange between the terrestrial biosphere and the atmosphere, and (4) identification and assessment of the potential and societal effects of possible human-induced climate change.

In the early years of NIGEC's operation, the Midwestern Regional Center had a broad research agenda including both aquatic and terrestrial ecosystems and many different disciplinary approaches. While this approach resulted in research projects in many relevant areas, there was little cohesion among these projects. In response to recommendations from DOE, each year the research themes of the Midwestern Regional Center have become more focused.

During this year, a primary goal of the Midwestern Regional Center was to focus upon the carbon dynamics of forests and agriculture, and their interactions with the atmosphere. A second goal was to increase the scientific inter-relationships of projects conducted through the Midwestern Regional Center and to increase the interactions of the investigators. A third goal was to increase collaborative efforts among NIGEC regional centers who share common research themes and where comparative analyses would prove valuable, as well as increasing collaboration with researchers investigating similar topics but supported by other sponsors.

Progress to Date

Since 1990 the Midwestern Regional Center has supported a total of 42 projects at 13 universities in 11 states. (The geographic area of the Midwestern Regional Center was much larger during 1990-1993.) Of those projects, 27 have been completed and 15 currently are on-going. As of June, 1995, a total of 73 journal articles, book chapters, and technical reports had been published and approximately that same number of manuscripts were reported as being either under review or in final stages of preparation. The Midwestern Regional Center always has emphasized the inclusion of students in projects. As of June 1995, 65 students, including undergraduates, masters and doctoral students have been supported by NIGEC projects through the Midwestern Regional Center.

Topics have included research on the effects of atmospheric aerosols on the radiative properties of the atmosphere. Further developing the methodology of integrated assessment and applying those methodologies has been the foci of four projects examining socio-economic aspects of climate change. Two projects made significant improvements in the methodologies of integrated assessment, while the other two evaluated consequences of climate change in the midwestern United States and in the former Soviet Union using economic models.

The Midwestern Regional Center has focused upon forests and agriculture. One project has been highly successful in identifying how elevated atmospheric carbon dioxide will alter the cycling of carbon from roots and mycorrhizae to soil microorganisms and in turn feed back on nitrogen availability and plant productivity. Three projects have investigated interactions between climate change and midwestern agriculture. One of these projects has parameterized and validated mechanistic models of trace-gas fluxes for agricultural soils representing major row-crop ecosystems of the Midwest. These other two projects have identified the sensitivities of (a) major commodity crops (corn, soybeans, wheat) and (b) specialized agriculture (fruits and vegetables) to possible climate changes in the Midwest. One project demonstrated the high rates of carbon sequestration in secondary growth forests in the Brazilian Amazon. Two projects are assessing the impacts of climate change on habitats of neotropical migrant birds and of mammals in the central and midwestern United States.

FY 1995 Research Themes

1. Research is needed to improve the quantitative, predictive understanding of possible consequences of global climactic and atmospheric change on terrestrial ecosystems, with an emphasis on the Midwestern region of the United States. The Midwestern Regional Center will focus upon forest and agricultural ecosystems. The focus of this research should be on identifying and quantifying probable direct and indirect effects of elevated atmospheric carbon dioxide concentrations and changes in means and extremes of climactic conditions on these natural and managed ecosystems.

2. Research is needed to improve the quantitative, predictive understanding of the global carbon cycle. The Midwestern Regional Center will focus upon quantification of sources and sinks of carbon dioxide in terrestrial ecosystems. The focus of this research should be on defining, analyzing, and modeling processes and mechanisms that contribute to spatial and temporal variation, and possible responses to global climatic change, in carbon dioxide sources and sinks in regionally-representative forest and agricultural ecosystems.

3. Research is needed to improve identification and assessment of potential economic and societal effects, either direct or indirect, from global climatic and atmospheric change, and how adverse effects might be modified by strategies for mitigating or adapting to climatic change. The Midwestern Regional Center will focus upon application of integrated assessment approaches to address the human dimensions of the two topics described above. The focus of this research should be on developing and applying models and methodologies for analyzing the implications of different policy options and factors contributing to, or affected by, global climate and atmospheric change.

FY 1996 Research Themes

The Midwestern Regional Center will focus upon quantification of sources and sinks of carbon dioxide in terrestrial ecosystems. This research should define, analyze, and/or model processes and mechanisms that contribute to spatial and temporal variation in carbon dynamics of forest and agricultural ecosystems at several different scales. This research also may examine possible impacts of global climate change on the carbon dynamics of forest and agricultural ecosystems and resultant feedback mechanisms that might occur. Another emphasis will be examination of the human dimensions of global environmental change, particularly quantification of economic and societal effects, such as institutional arrangements, resulting from and contributing to changes in the carbon dynamics of forest and agricultural ecosystems.

Effect of Climate Change on Species Distribution, Diversity, and Productivity in Grassland-Forest Habitats: A Regional Perspective

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Objectives: The ecological consequences of climate change are expected to be dramatic, but these effects depend on many interacting variables. These additional variables often contribute to uncertainty by creating additional linkages between atmospheric events and biota of interest such as crops or wildlife. For example, climatic shifts may affect ecosystems through several hierarchical pathways. These paths include the bottom-up effect of different net primary productivity on the output by plants in an area, intermediate-level changes in the structure of consumer communities as a result of shifting habitats, and spatial- or landscape-level changes in the fragmentation and distribution of habitats. Our aim is to obtain a qualitative sense of the direction of change in a number of these different components, allowing us to better elucidate the net effect that climatic change is likely to have on the ecosystem as a whole. We focus our study on grassland and forest habitats because the initial results show they will be most affected by climate change.

Thus, we asked how climate change would affect fragmentation, net primary productivity, and ecological characteristics (such as species composition) of communities. Since fragmentation of habitats often underlies any fragmentation of mammalian distributions, we first analyzed habitat distributions as a prerequisite to assessing the fragmentation of animal distributions. Net primary productivity is the foundation upon which many other characteristics of an ecosystem rest, and small changes in this variable may have significant consequences for the viability of consumer communities within an area. To understand the way in which communities respond to perturbations such as climatic shifts, it also is necessary to understand the processes that govern their current structure. Therefore, we also have focused on detecting patterns within communities of different species diversity.

Products: Products included models linking varied climatic scenarios to diverse components of forest or prairie ecosystems. A necessary component of these models is digitized maps

reflecting the geographic ranges of all plant communities and mammalian species currently occurring within the boundaries of our study region.

Approach: Our analyses relied on the use of a geographical information system (GIS, in this case PC ARC/INFO) to assess patterns of plant and animal distributions and productivity under different climatic conditions. We used two models to estimate the climate that would occur in Texas under increased CO₂: the Canadian Climate Centre (CCC) and Geophysical Fluid Dynamics Laboratory R30 (R30) models. Current vegetation patterns were determined by applying the Holdridge classification scheme to long-term climatic data from 354 weather stations. We then used the Holdridge formula to predict future vegetation associations around these weather stations based on the climatic predictions of the two models. Digitized maps of the ranges of mammalian species were overlaid on the vegetation maps and corrected for habitat, soil, and elevation requirements.

Fragmentation was assessed for the current distribution of forest and grassland habitats, those habitats occurring under the hotter/wetter climatic scenario (R30), and the hotter/drier scenario (CCC). In each case, habitats were analyzed separately, after being grouped into broad community types (e.g., forest and grassland), and after being grouped by Holdridge environmental categories (e.g., tropical, subtropical, and temperate). Several indices were used to provide a robust assessment of spatial patterns. For the fractal index, D, 10 grids with cells of increasing sizes were overlaid on the map of habitat types, the number of cells covering the range of the habitat was counted, and D was estimated (for each habitat) as the slope of a linear regression equation in which the size of the box predicted the number of occupied cells. Harmonic means of the distances among patches of each habitat were calculated directly from GIS maps: the distance to the nearest polygon of the same type was calculated for each polygon, and then these data were used to calculate the mean. Abundance of each habitat

was assessed by overlaying a single grid on the habitat maps for each scenario and simply counting the number of boxes in which each habitat occurred. Finally, the perimeter/area ratio of each habitat type was computed.

Community composition was analyzed for the 59 non-aquatic species of rodents occurring in forests and grasslands in Texas. The ranges of all rodent species (determined as above) were overlaid and the resulting polygons counted for species number. The taxonomy and life history characteristics of the species occurring in each species diversity polygon were determined, as well as the areas occupied by each. Our primary metric was the proportion and area of communities of a given species diversity occupied by a particular species. For communities of a particular size we had a single number for each species reflecting its occupancy of those areas. Thus, each species formed a row in an occurrence matrix where each column was a unique community size. Occurrence patterns were then analyzed under each individual scenario, and statistical analyses were used to test for changes in the distributions resulting from climatic change. We also tested for the effects that taxonomic group, size category, food type, and substrate preference had on the current distribution of species.

Net primary productivity (NPP) may be estimated from the percent cover in an area. We will employ a commercially available NDVI (normalized differential vegetation index) data set to estimate the cover of the study area. This raster data set will be converted to a vector ARC/INFO coverage compatible with our other data sets at the research center at Indiana University. The resulting cover will then be used to assign current cover indices to each of the weather polygons used in the other analyses. The meteorological information from each weather polygon will be used to develop a predictive equation where NDVI is the outcome variable and the weather variables are independents. The weather data from each climate change scenario can then be employed in this equation to predict cover under various conditions. The resulting coverages will be overlaid with the current coverage to determine a net change in NPP for each weather polygon. Statistical analysis of these areas will allow us to predict the net effects of each climatic scenario on the cover of the region as a whole, as well as the impact it has on geographical and

environmental subsets of the area.

Results to Date: (*Fragmentation*) There were significant increases in the abundance or coverage of tropical habitats from current conditions regardless of the level of precipitation (CCC {drier}: Kruskal-Wallis $\chi^2_{(appr.)} = 3.99$, $p < 0.05$; R30 {wetter}: $\chi^2_{(appr.)} = 4.40$, $p < 0.04$), and complete losses of warm temperate environments. Thus, regardless of changes in overall abundance of habitats, the models predict substantial changes in vegetative composition. There was also significantly higher variance among the coverages of tropical environments after climatic perturbations (drier conditions: Levine's median test, $t = 4.564$, $p < 0.02$; wetter conditions: $t = 3.114$, $p < 0.05$), although the variances between the CCC and R30 models did not differ. Compared to current conditions, therefore, we would expect a greater disparity in the sizes of different tropical habitats. However, there were no differences in the mean distributions of forests, despite the movement of individual habitat types (8 of 17 current habitats disappeared in a dry climate, 13 of 17 disappeared under wet conditions). We also compared the total proportion of boxes occupied by each habitat type under each scenario using log-likelihood ratios. Forest cover decreased significantly under the drier CCC climates ($G = 9.72$, $p < 0.005$) and increased significantly under the wetter R30 ($G = 217.7$, $p < 0.001$). Grassland decreased significantly under both climate change scenarios (CCC: $G = 292.9$, $p < 0.001$; R30: $G = 895.6$, $p < 0.001$). Thus, there were substantial changes in the abundances of habitats present after climatic changes, but these new types were distributed in essentially the same manner before and after climatic changes.

The degree to which the biomes or environment categories were fragmented (D) after climatic change did not differ from current conditions, nor between the $2\times\text{CO}_2$ scenarios (Kruskal-Wallis tests, $p > 0.25$ in all cases). The variance in fragmentation differed only for forests under CCC, where forest fragmentation was less variant (Levine's test; $t = 2.723$, $p < 0.05$). The average isolation (i.e., the harmonic means among polygons within each environment or habitat) was also not significantly different among any pairs of scenarios, nor did the variance in this statistic differ among scenarios.

There were no significant differences in mean fragmentation or isolation across all individual

habitat types among the three scenarios (Kruskal-Wallis tests, $p > 0.18$ in all cases). Likewise, there was also no difference in the magnitude of D between pairs of habitats occurring under both CCC and R30 (sign test, $n = 13$, $p = 0.08$). The variance in fragmentation among individual habitats did not differ significantly (Levine's test; CCC: $t = 0.43$; R30: $t = 0.60$). Likewise, the average isolation of the habitats under each scenario did not differ, nor did they have any statistically significant change in variance.

D for a particular habitat was significantly affected by the abundance of the habitat (Pearson's product-moment correlation; current: $r^2 = 0.48$, $p < 0.05$; CCC: $r^2 = 0.55$, $p < 0.006$; R30: $r^2 = 0.64$, $p < 0.004$). However, since there were several cases where the overall abundance of a habitat type changed but its fragmentation (D) did not, we feel confident this statistic measured some unique component of the spatial complexity present. Nevertheless, we also calculated fragmentation using the perimeter/area relationship of each habitat. Again, however, there was no significant effect of scenario on the distribution of this measure of fragmentation (Kruskal-Wallis, $\chi^2_{(appr.)} = 0.68$, $p > 0.70$) or on its variance (Levine's tests, $|t| < 0.50$).

(Community Structure) The distribution of sizes of rodent communities was altered after climatic change occurred. Currently, the lowest diversity communities contain 9 species and the most diverse contain 41 species. Under both climatic scenarios the range of community sizes expanded, to low diversity communities with 7 species and high diversity communities with 46 species. The additional high diversity communities were derived primarily from those communities with high diversities under current conditions: the areas occupied by 36-40 species fell from $73.4 \times 10^3 \text{ km}^2$ to $11.4 \times 10^3 \text{ km}^2$ under CCC and to $4.3 \times 10^3 \text{ km}^2$ under R30, while communities with 41-46 species occupied $39.1 \times 10^3 \text{ km}^2$ under CCC and $16.2 \times 10^3 \text{ km}^2$ under R30. Under wetter conditions the geographic location of these high diversity communities remained unchanged, while under the dry scenario there was a northward movement. Under current conditions, the areas of greatest diversity occurred in transitional dry-moist forest. Under both climate change scenarios, lower montane grassland-forest transitional habitats were the loci of greatest

diversity. There was also a substantial redistribution under R30 into communities containing a relatively low number (15) of species.

Despite these differences, however, the overall distributions were similar. There was a statistically significant similarity between the area of Texas occupied by communities of a particular species richness under each of the different scenarios (Pearson's product-moment correlation; current with CCC: $= 0.379$, $p < 0.05$; current with R30: $= 0.563$, $p < 0.01$; CCC with R30: $= 0.552$, $p < 0.01$). In addition, none of the distributions of community sizes were normally distributed (Kolmogorov D statistic; Current: $D = 0.1239$, $p < 0.01$; CCC: $D = 0.1711$, $p < 0.01$; R30: $D = 0.2642$, $p < 0.01$). Thus, while each scenario was similar, none was structured in a random (normal) pattern. This observation implies that the communities are structured by non-random processes that do not operate equally over the breadth of observed community sizes.

However, the way individual species were distributed among communities of a particular size was similar across different climatic conditions: the proportion of polygons occupied (P_o) by the rodent species were significantly correlated with each other ($p < 0.05$ in all cases). Thus current communities of a particular species richness would be expected to have the same general composition regardless of whether the climatic shifts resulted in a wetter or drier environment. Within each climatic scenario there were generally differences in the composition of communities that had different diversities. For example, there was no correlation between the P_o of CCC communities containing 10 and 21 species. There was also no effect of similarity in community size: those communities that had similar numbers of species were no more likely to be correlated than those with vastly different species diversity. Species present in only a single community class did not generally occur in the highest diversity communities. Widely distributed species (those occurring across a wide range of species richness classes) were generally similar species under all conditions.

Occurrence patterns under current conditions were not well-predicted by categorical variables reflecting taxonomic affiliation, body size, food type, or preferred substrate. The only significant predictor (from analysis of variance) was food

type, and this variable did not predict patterns across all species diversity intervals. Rather, only communities with intermediate levels of diversity showed a significant effect of food type. In these communities, the differences were likely caused by differences between granivores and omnivores, the only two categories to have significant differences among their means (Scheffe's multiple comparisons test, $p < 0.05$).

Summary: Climatic shifts do not generally result in different fragmentation patterns in habitats at this regional scale, despite the substantial movements of habitats to new areas, and the concomitant replacement of old habitats with new types. Changes in the degree of moisture predicted by different models do not create differences in the rank-distributions of habitats, although moisture mediated shifts in the relative abundance and composition of forests and grasslands may occur. Since much current fragmentation is caused by direct anthropogenic activity and is, thus, subject to short-term interdiction, our results suggest fragmentation may be controllable to a very high degree.

After climatic change, the way species are distributed within communities of a particular species diversity generally remains the same. However, the habitat types in which diversity is greatest differs from current conditions. In both climate change scenarios diversity is greatest in the same habitat type (grassland-forest transitions), implying that the precipitation differences among the models does not directly affect diversity. The basic distribution patterns, however, suggest that internal processes may govern the composition of individual

communities. Indeed, there are few consistencies to discriminate among the species that occupy species-rich or species-poor communities, and patterns among such categories are not well predicted by differences in life-history attributes. We infer that detailed scrutiny of particular species and their possible interactions may help to clarify the factors determining local community diversity.

We hypothesize these counterintuitive results may be due to characteristics of Texas that make it a biologically diverse area: steep environmental gradients, both a north/south temperature continuum and an east/west moisture gradient. Under shifting climates, the intersection of these influences allows for a continuous progression to new habitat types, but retains the spatial diversity of the original condition. Thus, climatic change may affect fragmentation of more environmentally homogeneous grasslands and forests to a greater extent than more environmentally diverse areas. Since biological diversity at a regional scale is generally enhanced by environmental diversity, specialized species occurring in low diversity regions may be particularly sensitive to climatic change.

Manuscripts in Preparation: 1) Habitat fragmentation and climate change. and 2) Community structure in changing environments.

Presentations: Effect of global climate change on biodiversity in Texas. Baylor University, TX, April 1995

Student participation: Joshua O. Seamon, postdoctoral researcher, 100%

The Drop Size-Dependent Nature of Cloud Chemistry and its Relationship to the Processing of Atmospheric Aerosols and Trace Gases

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Objective: Experimentally determine the extent of chemical heterogeneity present among cloud drops formed in a variety of environments with different cloud types and pollutant levels. Determine how major ion concentrations and acidity vary with drop size. Use this information, combined with measurements of variations of sulfur and oxidant species, to determine how the rate of in-cloud sulfur oxidation varies with drop size. Determine how observed variations in drop composition with drop size influence removal efficiencies for individual species during accretional growth of precipitation.

Products: A data set, comprised of results of a survey of size-dependent cloud chemistry at sites across the U.S., containing information on variations across the cloud drop size spectrum of concentrations of major ions, sulfur species, oxidants, and drop acidity. The data set includes a variety of cloud types and pollutant levels. The data set will be used to evaluate how non-uniform cloud drop chemistry affects aqueous phase sulfate production rates and scavenging of individual chemical species during accretional growth of precipitation.

Approach: Various combinations of cloudwater collectors were used to sample clouds and fogs at several sites including locations along the Pacific coast (stratus clouds), in California's central valley (radiation fog), in the Appalachian Mountains (frontal and orographic clouds), and in the Rocky Mountains (frontal clouds). The collectors employed included a two-stage ETH cloud impactor, a three-stage IESL cloud impactor, a Caltech Active Strand Cloudwater Collector 2 (CASCC2), and a Caltech Active Strand Cloudwater Collector (CASCC) with a size-fractionating inlet. During many experiments, measurements were also made of aerosol and trace gas chemistry to evaluate their influence on the size-dependent nature of cloud drop chemistry.

Two versions of the ETH cloudwater impactor were used for collecting size-fractionated samples of cloudwater. The first was the prototype instrument developed at ETH by the

principal investigator. This multiple-jet, two-stage cascade impactor was designed to provide 50% lower size cuts of 3 and 10 μm at a flow rate of 418 l min⁻¹. The impactor is constructed of Plexiglas but features Teflon impaction plates. A precipitation shield mounts above the impactor inlet as needed to prevent entry of precipitation. An additional impaction stage on top of the first jet plate ensures only cloud drops penetrate to the sampling stages of the impactor. A second, modified version of this collector, the IES cloud impactor, was constructed and used in many of the sampling campaigns. This modified version employs interchangeable jet plates allowing different size cuts to be selected to provide more flexibility in partitioning the cloud drop size spectrum during sampling.

The IESL cloud impactor collects three independent drop size fractions of cloudwater simultaneously. It also features interchangeable size cuts to permit analysis of different portions of the cloud drop size spectrum. The flow rate through the IESL impactor is more than three times the flow rate through the ETH impactor, permitting more complete analysis of trace species.

The CASCC2 was used as a reference for bulk cloudwater chemistry in some of the studies where electric power was available. The CASCC2 is an active collector that utilizes an inclined bank of 508 μm Teflon strands as collection surfaces. The 50% lower size-cut for this collector has been estimated as 3.5 μm . The design of the size-fractionating CASCC is similar, although it is larger than the CASCC2, features a higher flow rate, and includes a separate sampling section in the inlet which permits collection of large cloud drops. The size-fractionating CASCC was used to collect pairs of small (diameters between 3.5 and 23 μm) and large (diameters larger than 23 μm) cloud drop samples at a number of locations.

Results to Date: Comparisons of the chemical composition of cloud drop fractions collected with the cloud samplers reveal differences between the composition of small and large cloud drops. The small cloud drop fraction tends to be more

acidic than the large drop fraction. The pH differential has been observed in samples representing a wide range of acidities (pH values from less than 3 to nearly 7). The magnitude of the pH differential varies substantially between different cases, ranging from as little as a couple tenths of a pH unit to more than a full unit.

Distributions of major ions across the cloud drop size spectrum often reflect their distribution across the precursor aerosol size distribution. Species associated with submicron aerosol particles, produced from gas-to-particle conversion processes, tend to be enriched in small cloud drops. This pattern has been observed for ammonium, nitrate, and sulfate. Species associated with coarse, mechanically generated particles such as soil dust and sea salt tend to be enriched in larger cloud drops. Ions enriched in large drop fractions collected at the various sites include calcium, sodium, and chloride. These findings are consistent with expectations that smaller aerosol particles grow to produce smaller cloud drops, while larger particles produce larger drops. Analysis of samples collected with the three-stage IESL cloud impactor revealed U-shaped concentration profiles (higher in small and large cloud drops than in intermediate drop sizes) for some samples but decreasing concentrations with drop size for others.

The observed variation in drop composition across the drop size spectrum requires that we reassess our conclusions about the role of clouds and fogs in a number of processes. Rates of sulfur oxidation, contributions to wet and occult deposition, and health effects of inhaling urban fogs can all be affected by these variations.

Rates of sulfur oxidation in the aqueous phase depend strongly on the concentrations of S(IV), oxidants, and catalysts. The rate of oxidation by hydrogen peroxide is fairly independent of pH over the pH range observed in most cloud and fog droplets. Rates of oxidation by ozone and oxygen (catalyzed by Fe(III) and Mn(II)) are strong, nonlinear functions of pH. In environments where hydrogen peroxide concentrations are low, or after depletion of initial hydrogen peroxide concentrations through reaction, the rate of sulfur oxidation is likely to be governed strongly by pH and catalyst distributions across the drop spectrum. Since the larger drops tend to have higher pH values,

we expect them to promote faster rates of sulfur oxidation if concentrations of the other relevant species are equal. Because of the nonlinear variation of the oxidation rate with pH, the average cloudwater pH is a poor predictor of the net sulfur oxidation rate in the actual, distributed cloud drop population. The magnitude of the error in predicting sulfate production will depend on the degree of chemical heterogeneity that exists across the drop spectrum coupled with the distribution of liquid water content across the spectrum. Based on typical cloud drop compositions and liquid water distributions from our data set, it is apparent that use of average cloud drop pH to predict rates of S(IV) oxidation by ozone can easily produce estimates which are only a fraction of the rates in a real, chemically heterogeneous cloud. The chemical differences between large and small cloud drops could account for at least a 20% enhancement in the rate of S(IV) oxidation by ozone for one-third of the cloudwater samples collected. For 8% of the cloudwater samples, the rate was estimated to increase by more than 100%. Measurements of non-uniform distributions of acidity and iron across the cloud drop size spectrum suggest that enhancement of the rate of the iron-catalyzed oxidation of S(IV) by oxygen is generally greater than observed for the ozone pathway.

Real clouds contain more than two chemically distinct drop populations, as revealed by measurements made with the three-stage IESL cloud impactor. In addition to variations in pH as a function of drop size, it is unlikely that all drops of the same size will have the same acidity. A wider distribution of drop compositions can support even faster sulfur oxidation rates.

Hydrogen ions are produced as S(IV) is oxidized. Since S(IV) oxidation by several pathways is pH-dependent, production of hydrogen ions can decrease the rate of S(IV) oxidation over time. If the cloudwater possesses significant buffering capacity, however, the drop in pH will be mitigated, permitting faster rates of sulfate production to continue. Acid titrations of a few of the collected fog and cloud samples revealed the presence of significant buffering capacity in some high pH samples. Further investigation of the buffering capacity of fog and cloud samples is needed to determine their potential for supporting sulfate production in peroxide limited environments. Measurements of buffering capacity are particularly important for determining whether a few large, alkaline drops in a cloud

can oxidize substantial amounts of sulfur.

Future work on the effects of chemical heterogeneity among cloud drop populations on sulfur oxidation should focus on speciation of S(IV) in solution. Our results indicate that concentrations of S(IV) vary across the cloud drop size spectrum in a complex way that cannot be predicted from knowledge of drop acidity and gaseous sulfur dioxide concentrations alone. Formation of S(IV)-aldehyde complexes, including hydroxymethanesulfonic acid (HMS), is drop size-dependent. Distributions of HMS across the drop size spectrum are related to distributions of drop acidity and formaldehyde as a function of drop size and can be explained through analysis of the timescales for multiple sinks (aldehyde complexation vs. various oxidation pathways) of dissolved sulfur dioxide in the drops. Under certain conditions when both pH is high (approximately 6 or greater) and formaldehyde concentrations are high, formaldehyde complexation of S(IV) can limit the rate of S(IV) oxidation.

In addition to affecting rates of aqueous phase sulfur oxidation, chemical heterogeneity among cloud drop populations will result in non-uniform addition of sulfate to the cloud condensation nuclei dissolved within the drops. This is an important factor when considering the ability of sulfate aerosols to perturb climate, either through direct scattering of radiation or indirectly via their ability to act as cloud condensation nuclei in subsequent cloud formation cycles.

The distribution of chemical species across the cloud drop size distribution also carries important implications for removal of atmospheric pollutants by wet deposition. Outside the tropics, most precipitation forms through processes involving the ice phase. In mixed-phase (ice-water) clouds which produce much of this precipitation, accretional capture of supercooled cloud drops by growing ice crystals (riming) is a key step in transferring pollutants to precipitation for removal

via wet deposition. One factor affecting the degree of riming occurring during precipitation growth is the size distribution of cloud drops. Larger cloud drops are captured more efficiently by the ice crystals because of their greater inertia. Separate work indicates that cloud drops with diameters in the range of 20 to 40 μm contribute most to accreted ice crystal mass. The composition of cloud drops in that size range, therefore, is a primary determinant of the resulting precipitation composition. Since we have observed many species associated with anthropogenic emissions, such as sulfate and nitrate, to be enriched in small cloud drops which are captured with only limited efficiency, it appears that even accretional growth of precipitation is not as efficient at removing many of these pollutants from the atmosphere through wet deposition as we would predict based on a simple analysis of bulk cloudwater chemistry.

Publications:

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Global Atmospheric Behavior of Polychlorinated Biphenyls

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Objectives: In North America, production of polychlorinated biphenyls (PCBs) stopped in mid-1977 (1). Since that time, PCB concentrations have decreased in fish, seal blubber, polar bear tissue, and herring gull eggs with half-lives of 6 to 15 years (2-6). Sediment cores from various lakes also show decreasing concentrations since 1970 (7-8). Atmospheric PCB concentrations, however, have not changed (9). This is puzzling; it is unclear how the concentration in environmental sinks could decrease while the concentration in the transport medium (the atmosphere) stays constant.

There are two possibilities: (a) Atmospheric PCB concentrations have decreased since PCBs were banned, but this change has not been detected. (b) PCB concentrations have actually remained constant over the past 15 years. There are two reasons why a real decrease in PCB concentrations could have escaped detection. First, over the last 25 years, the methods used to analyze PCBs have improved, and thus, older data may not be comparable to newer data. Second, PCB concentrations in the Great Lakes region have been shown to exhibit large seasonal variations (10-11). For example, Hermanson and Hites (11) showed that atmospheric PCB concentrations increased by almost two orders of magnitude from winter to summer. Therefore, any comparison of PCB concentrations from different years should have included a correction for atmospheric temperature; the older measurements did not. Of course, it is also possible that no actual change in atmospheric PCB concentrations has occurred. If this stability of atmospheric PCB concentrations is real, it could have important ramifications on regulatory decisions in the future.

The objective of this study was to measure the atmospheric concentrations of PCBs over an extended period of time at a site where local sources and temperature variations were minimal. By collecting air samples at a remote site with these characteristics, we hoped to detect any long-term trends in atmospheric PCB concentrations. Thus, we have collected air samples at Bermuda for a one-year period using

a technique which avoids local PCB sources. From these data, we have been able to assess the long-term PCB concentration trends, to determine PCB's atmospheric residence times, to estimate the flux of PCBs to and from the atmosphere, and to examine the importance of different source regions on PCB concentrations.

Products: See Publications Section below.

Approach: All samples were collected at Tudor Hill on the west coast of Bermuda between May 1992 and July 1993. A 23 m sampling tower, owned by AEROCE (the Atmosphere-Ocean Chemistry Experiment), is located at this site, approximately 50 m in from the shore. Our sampler was mounted on the north side of this tower. We collected our samples using a modified high volume air sampler. The sampler head was mounted near the top of the tower and connected with aluminum tubing to a pump and flow meter housed at the bottom of the tower.

We were interested in background atmospheric concentrations of PCBs; therefore, we wanted to avoid any contamination of our samples by local influences. This was accomplished using a technique called "sector sampling": Samples were collected only when the wind was blowing off the open ocean and not when the wind had passed over Bermuda. The air sampler pump was connected to a computer which received data from meteorological instruments and provided power to the pump only when the wind speed was greater than 2 m/s and the wind direction was between 180° and 330°.

Samples were collected by pulling air first through a glass fiber filter which collected particles then through a polyurethane foam (PUF) plug which collected vapor-phase analytes. The PUF plugs were 10 cm in diameter by 10 cm long. Sample sizes ranged from 1000 to 2000 m³. Prior to sampling, the glass fiber filters were cleaned by heating them at 450°C for 8 hours to remove organic material adsorbed onto the filter. The PUF plugs were cleaned by rinsing them thoroughly with tap water, then rinsing them with acetone. They were extracted in a Soxhlet apparatus for 24 hours with acetone, then for 48 hours with

petroleum ether. Finally, the PUF plugs were rinsed with fresh petroleum ether, allowed to air dry, and stored in sealed glass jars until they were shipped to Bermuda. Immediately prior to shipping, the PUF plugs were placed in glass cylinders, wrapped in aluminum foil and placed in aluminum cans, which were sealed by black plastic tape.

The sampling media were shipped to the Bermuda Biological Station by an overnight delivery service. They were then transported by moped to the sampling site, where they were stored in a clean room until they were used for sample collection. At this point, a technician brought the sampler head into the clean room, installed the glass fiber filter and PUF plug using clean plastic gloves, then carried the assembly to the top of the tower. After the sample was collected, the sampler head was again brought into the clean room, the glass fiber filter and PUF plug were wrapped in their original aluminum foil, the PUF plug was placed in its aluminum can (which was again sealed with black plastic tape), and the sample was stored in a freezer. Glass fiber filters and PUF plugs were shipped to Bermuda in sets of 8 to 10. One set from each batch was used as a field blank; it was placed in the sampler for 24 to 48 hours with the pump turned off. Once all samples from a batch were collected, they were returned to the Biological Station by moped and shipped back to Bloomington.

Each batch of samples was analyzed immediately upon its arrival in Bloomington. Internal standards consisting of known amounts of PCB congeners 30 and 204 (2,4,6-tri- and 2,2',3,4,4',5,6,6'-octachlorobiphenyl, respectively) were injected onto each PUF plug. The PUF plug was then placed in a Soxhlet apparatus and extracted with petroleum ether for 24 hours. These extracts were cleaned up on 2 g columns of 6% water deactivated silica gel. PCBs were eluted with 25 mL of hexane and 5 mL of 10% dichloromethane in hexane. These fractions were combined, solvent-exchanged to hexane, and reduced in volume to 1 mL. Recovery of the analytical method was checked using spiked PUF plugs; recovery for the individual congeners ranged from 85 to 105%. The extracts of a few of the samples were divided in half and each subjected to the clean-up and analysis procedures to determine reproducibility. The measured concentrations for the duplicates were within 10% of each other. The glass fiber filters

were not extracted for the majority of the samples because preliminary experiments showed that any PCBs trapped on these filters were below our limits of detection.

The PUF extracts were analyzed by gas chromatography with electron capture detection (GC-ECD) on a Hewlett-Packard 5890A gas chromatograph with a 30 m, 250 μ m i.d., 0.25 μ m phase thickness, DB-5 column (J & W Scientific, Folsom, CA). The temperature program was 40 to 140 °C at 10 °C/min., 140 to 230 °C at 0.8 °C/min., 230 to 280 °C at 10 °C/min., and a 5 minute hold at 280 °C. GC peak assignments and relative response factors were determined for each PCB congener using the method described by Mullin (12), which was based on a DB-5 GC column such as the one we used in this study. The method was calibrated using a mixture of Aroclors 1232, 1248, and 1262 in a 25:18:18 ratio; these standards were acquired from the U.S. Environmental Protection Agency in Cincinnati. Our gas chromatograms matched those given in reference 12.

The relative response factors for each PCB congener were determined each day that samples were analyzed and used to calculate the amount of each congener present in the samples and field blanks. About 80 GC peaks were quantified; these represented a total of 119 congeners, some of which co-elute. In order to determine the concentration of each congener in the sample, the amount of a given congener measured in the sample was corrected by subtracting the amount of that congener in the field blank; the result was divided by the volume of air sampled. Sample amounts were corrected in this manner because we judged that field blank amounts were too high to ignore. Signal-to-blank ratios were typically in the range of 10:1 to 60:1, but for a few cases they reached as low as 5:1. The variation in this ratio was due mainly to differences in the sample size and concentration; field blank amounts were all in the range of 50 to 100 ng total PCB. We operationally defined the limit of detection as the amount of PCB in the sample that gave a signal-to-blank ratio of at least 3:1. These detection limits varied depending on the level of each congener present in the field blanks; they ranged from 0.0003 to 0.006 ng/m³, with most congeners in the range of 0.001 to 0.003 ng/m³.

A total of 34 samples were collected. Of these, three had PCB concentrations which were at or

below the detection limit. We did not include these samples in our data analysis. Two other samples were also omitted because they had concentrations which were much higher than the other samples and exhibited signs of being contaminated by an unknown source.

Results: Concentration Trends. The average total PCB concentration in our air samples was 0.38 ng/m^3 ; this is a number density of $7.6 \times 10^5 \text{ cm}^{-3}$. Average concentrations of individual PCB congeners ranged from 0 to 0.08 ng/m^3 . Most of the air samples had similar congener profiles; that is, the relative amount of each congener did not change from sample to sample. The trichloro and tetrachloro PCBs are most prevalent in the Bermuda samples. This profile is similar to Aroclor 1242 with the exception that congener 66 is somewhat more prevalent in the Aroclor mixture (13).

It is interesting to compare our concentration data with other concentrations measured in Bermuda over the past twenty years. There is a great deal of scatter in these data, possibly because the samples were collected during different seasons of the year. In addition, there are problems comparing new measurements and those made twenty years ago. During this time, the methods used to analyze PCBs have changed. For example, PCBs are now analyzed using capillary column gas chromatography, but this technique was not available prior to 1980 when packed columns, which gave poor resolution, were used. The methods for quantifying PCBs have also improved. PCBs were produced in the United States as commercial Aroclor mixtures. Many measurements in the past calculated a total PCB concentration based on matching the chromatographic "fingerprint" of the sample with that of different Aroclors. This method did not allow for the quantification of individual congeners, and it did not account for any changes in the congener profile between the PCB source and the site where the sample was collected. However, we emphasize that we are comparing total PCB concentrations and that the accuracy of total PCB values reported in the literature in the past is reliable, even though individual congeners could not be specified.

No obvious trends in total PCB concentration over time were apparent from visual inspection of the data, so we analyzed these data statistically to determine any trends. A linear regression

between the logarithms of the concentrations and time gave a correlation coefficient (r) of -0.067 , which is not significant. This indicates that there is no trend in PCB concentration as a function of time. The 95% confidence limits of this regression indicated that the maximum decrease during the last 25 years was a factor of 2.1. This corresponds to a maximum annual decrease of 3%. In other words, if the PCB concentration had decreased by more than 3% per year, we would have detected this change by our analysis. This percentage implies that the half-life of PCBs in the atmosphere is greater than 23 years; we would have detected a shorter half-life.

Residence Times. One factor affecting the transport of PCBs is their atmospheric residence times; that is, the average time that a particular molecule spends in the atmosphere before being degraded or removed to another environmental compartment. Atmospheric residence times can be determined using a method described by Junge (14). This method uses the variability of trace gases in the atmosphere to determine their residence times. Junge collected data showing that gasses which have high relative standard deviations of their mixing ratios (such as water vapor) have short atmospheric residence times.

There are several limitations to applying this method to PCBs. This method assumes that the environmental sinks of PCBs are evenly distributed throughout the troposphere. We believe that this is true. PCB sinks include deposition to water, soil, and vegetation and homogeneous gas-phase reactions such as reactions with OH radicals (15); clearly, these processes are uniform throughout the troposphere. In addition, the application of this method requires that samples be collected over a period of at least one year because many compounds exhibit an annual cycle. Our samples were collected over 14 months. Also, Junge stipulates that samples should be collected from many locations around the world. Our samples were collected at only one site, but Bermuda receives air both from the east and from the west. For this reason, we are confident that our data can be used to calculate realistic atmospheric residence times of PCBs.

We used our data to calculate residence times for those PCB congeners detected in at least six samples. To the best of our knowledge, this is the first time that residence times for individual PCB congeners have been reported. Most of

these residence times are in the range of 40 to 75 days, which agree with the residence times reported by Bidleman et al. (16), but are shorter than the 190 days reported by Atlas and Giam (17).

We calculated the mean and standard deviation of the residence times for each homologue class (given number of chlorines) and noted that the atmospheric residence time decreases with increasing level of chlorination. This decrease is statistically significant; the correlation coefficient (r) between the residence time and the level of chlorination is -0.86 , which is significant at the 99% level. Although we are unsure of the exact cause of this relationship, it is probably due to the vapor pressure trends of these compounds. The vapor pressure of each homologue class decreases by a factor of 5 to 10 with the addition of one chlorine atom (18). When PCBs volatilize from their sources and enter the atmosphere, they equilibrate between the vapor and particle phases. As the wind carries these compounds away from their sources, the particles and their adsorbed PCBs are more likely to be removed by wet and dry deposition. PCBs with more chlorines have lower vapor pressures and are more likely to be associated with particles near their source, and therefore, these more highly chlorinated PCBs are more easily removed from the atmosphere than less chlorinated congeners. Although the fraction of PCBs associated with particles is small for all homologue classes, it is larger for highly chlorinated PCBs, and this may cause the decrease in residence time for these compounds.

Atmospheric Fluxes. As shown above, there has been no detectable change in atmospheric PCB concentrations at Bermuda in the past 20 years; in other words, atmospheric PCB flows are at steady state. We have also shown that these compounds have atmospheric residence times in the range of 40 to 75 days. Using these two pieces of information it is possible to calculate the flux of PCBs into and out of the atmosphere. If we assume that the background PCB concentration is 0.3 ng/m^3 throughout the entire atmosphere, and that the volume of the atmosphere (at STP) is $4 \times 10^{18} \text{ m}^3$, we can calculate a total atmospheric load of $1.2 \times 10^6 \text{ kg}$. If this amount of PCB flows out of the atmosphere every 70 days (our calculated residence time for the most prevalent PCBs) and the surface area of the earth is $5 \times 10^{14} \text{ m}^2$, the atmospheric flux of PCBs is $13 \mu\text{g m}^{-2} \text{ yr}^{-1}$.

Since the system is at steady state, the net flux of PCBs must be zero. That is, the flux of PCBs into the atmosphere from water, soil, and vegetation must equal the flux of PCBs out of the atmosphere. Our flux of $13 \mu\text{g m}^{-2} \text{ yr}^{-1}$ is therefore an estimate of both the flux into and out of the atmosphere, and it can be compared with fluxes reported in the literature in either direction. Perhaps the most important comparison we can make is with recent flux measurements made in the North Atlantic by Iwata et al. (19). They measured both air and surface-seawater concentrations of PCBs and estimated the flux for individual PCB congeners and total PCBs. They made their estimates assuming two different scenarios: (a) all PCBs in the seawater were dissolved and (b) all PCBs in the water were adsorbed onto particles. In the first case, they calculated a flux of -5.5 to $+22 \mu\text{g m}^{-2} \text{ yr}^{-1}$ to the North Atlantic (the negative value indicates that PCB transfer occurs from the water to the air). In the second case, they calculated a flux of 3.5 to $31 \mu\text{g m}^{-2} \text{ yr}^{-1}$ to the sea. Both of these ranges include our value of $13 \mu\text{g m}^{-2} \text{ yr}^{-1}$. In fact, the ranges they calculated for the Chukchi Sea, Bering Sea, Gulf of Alaska, North Pacific, and Mediterranean Sea also include our value. Iwata's measurements of fluxes in the southern hemisphere yielded lower values, due to lower PCB concentrations in both the air and water.

We can also compare our flux with those measured at other locations. Our flux is similar to $10 \pm 3.4 \mu\text{g m}^{-2} \text{ yr}^{-1}$ found by Hermanson et al. (20) for deposition to Lake Michigan. It is higher than the flux of 0.8 to $3.1 \mu\text{g m}^{-2} \text{ yr}^{-1}$ found by Swackhamer and Armstrong (21) for the net deposition to remote lakes in Wisconsin, and it is much higher than 0.2 to $3 \mu\text{g m}^{-2} \text{ yr}^{-1}$ found by Atlas and Giam (22) for deposition to Enewetak Atoll in the North Pacific. However, it is significantly lower than 300 to $800 \mu\text{g m}^{-2} \text{ yr}^{-1}$ estimated by Thome et al. (23) for volatilization from the South Bay of the North Sea and $1500 \mu\text{g m}^{-2} \text{ yr}^{-1}$ of dry deposition found by Holsen et al. (24) in Chicago. Achman et al. (25) found fluxes of 4.7 to $470 \mu\text{g m}^{-2} \text{ yr}^{-1}$ for volatilization from Green Bay, a wide range which includes our value. The wide variation of these reported flux measurements, as well as the direction of the flux, may indicate that some areas are net sources of PCBs and other areas are net sinks.

Air Trajectories. We know that PCBs are transported through the atmosphere (17), but we

would like to know where the air parcel with a given concentration of PCBs came from. Air trajectory analysis is a method by which the path of an air parcel arriving at a certain point at a certain time can be traced backward for several days (26). Air trajectories have proven useful for establishing source/sink relationships for many inorganic ions (27-30). However, organic compounds have been more difficult to track in this manner. Hoff et al. (31) were able to use air trajectories to show that several air parcels arriving in Ontario, which showed elevated organochlorine concentrations, originated in the southern United States. However, Hoff's PCB concentrations showed little systematic variation with air trajectories; atmospheric temperature was a much more important factor in determining the concentration (31). The effect of air temperature has also been noted by Hermanson and Hites (11) for several sites in Bloomington, Indiana, and by Manchester-Neesvig and Andren for a site in Northern Wisconsin (10). These researchers found that PCB concentrations increased with increasing temperature, even if known PCB sources were over 100 km away. By choosing Bermuda, a site far removed from PCB sources, and by using sectorized sampling to avoid any local contamination, we hoped to minimize temperature effects and to examine the effect of different air parcel sources and meteorological parameters on atmospheric PCB concentrations in Bermuda.

We used air trajectories provided by John Merrill at the University of Rhode Island. The air trajectories are isentropic and follow constant potential temperature surfaces. "Isentropic" means that the air parcel has constant entropy along its entire path and that it is subjected only to adiabatic processes. "Potential temperature" is the temperature which the air parcel would have if it were expanded or compressed adiabatically from its existing pressure to the standard pressure of 1000 mbar. If entropy is constant then the potential temperature is also constant and *visa versa* (32). The air trajectories are determined by first calculating the constant potential temperature surface based on data from satellites and balloons, then using wind speed and wind direction data along those surfaces to calculate the trajectory.

We looked at several parameters in attempting to establish a relationship between air trajectories and PCB concentrations at Bermuda. These included the average pressure (altitude) at which

the air parcel traveled, the minimum pressure (maximum altitude) experienced during the trajectory, the length of the trajectory, the straight-line distance between the beginning and end of the trajectory, the number of days the air parcel spent over land, the air temperature at the site where the air parcel last passed over land, and the trajectory angle (the angle between due north and the point of origination of the air trajectory, where Bermuda is the vertex of the angle). Many of these parameters were strongly correlated with each other. We also included the water temperature at Bermuda as a parameter; it was not correlated to any of the air trajectory parameters.

Using the step-wise procedure in the Statistical Analysis System (SAS), we evaluated the various parameters given above as predictors of the atmospheric PCB concentration at Bermuda. This SAS procedure performs a multiple regression analysis in which parameters are added to (or subtracted from) the regression depending on the probability that each parameter affects the overall result. For those parameters that are significant predictors of the PCB concentration, the coefficient of determination of each parameter is calculated. This analysis was performed for each of the PCB congeners and for the total PCB concentration. Only four parameters had significant prediction ability for many congeners: water temperature, minimum pressure, and the sine and cosine of the trajectory angle. Because the minimum pressure was strongly correlated with the sine and cosine of the trajectory angle, we could not use it in the same regression as the other two variables. Therefore, we performed two multiple regression analyses on the PCB congener concentrations. The first used water temperature and minimum pressure as the independent variables; this analysis did not show a significant relationship between concentration and the meteorological parameters for most of the PCB congeners. (In actuality, the water temperature may be correlated with air concentration, but our water temperature measurements, made every two weeks, may not have been recorded with high enough frequency to discern this effect.) The second multiple regression analysis used the sine and cosine of the trajectory angle as the independent variables. This analysis showed that these parameters were predictors of the PCB congener concentrations, although the overall level of significance was not high.

Based on this statistical hint, we noted that those samples having a trajectory angle between 0° and 200° have higher average PCB concentrations than those with a trajectory angle between 270° and 360°. A statistical analysis of these data shows a significant difference between the two groups; the t-statistic is 3.5, indicating a significant difference at the 99% confidence level. The higher concentration samples originated over the eastern Atlantic and Africa, while the lower concentration samples originated over the United States. This is somewhat surprising, because more industrialized countries are often thought to be more significant sources of PCBs to the atmosphere. However, such data are not without precedent. During an Atlantic cruise in 1984, Church and coworkers (14) collected several air samples and analyzed them for PCBs. The sample with the highest PCB concentration was one which had been collected off the west coast of Senegal (in far western Africa). This indicates that non-industrialized regions may be more important sources of PCBs than commonly believed.

The air trajectories arriving at Bermuda exhibit a seasonal trend. Much of the meteorology in the north Atlantic is influenced by a pressure system called the Bermuda high (33). As the Bermuda high moves north in the summer, air arriving at Bermuda come from the east. Conversely, as the Bermuda high moves south in the winter, air arrives at Bermuda from the west. (Note that we are discussing the origin of the air parcel, not necessarily the local wind direction at the sampling site.) Because of this seasonal effect on the trajectory direction, air parcels arriving from the east have usually originated over Africa or Europe during the summer when temperatures are high and PCBs can volatilize more easily. Air parcels arriving from the west, however, usually have originated over North America during the winter when temperatures are colder and PCBs cannot volatilize from their sources as readily. Thus, the differences in PCB concentrations may also be the result of temperature differences at the various sources.

We also looked at the congener profiles of the samples under both air flow regimes. Although the absolute concentrations were higher in the eastern samples, the congener profiles were similar in both data sets. The similarity of congener profiles in eastern and western samples indicates that the sources and transport

mechanisms controlling PCB concentrations at Bermuda are similar for both eastern and western samples.

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- Publications:**
- Diurnal variations in atmospheric concentrations of polychlorinated biphenyls and endosulfan: Implications for sampling protocols, *Environmental Science and Technology*, submitted; with J. C. Wallace.
- A system to measure rate constants of semi-volatile organic compounds with OH radicals, *Environmental Science and Technology*, in press; with P. N. Anderson.
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Incorporating Learning into an Integrated Assessment Model of Climate Change

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Objectives: The basic goal of the is to enhance integrative assessment capabilities by incorporating uncertainty and learning into dynamic models of economic growth, CO₂ accumulation and climate change. The general problem is how to use an integrated assessment model to determine the optimal control of emissions in a situation where greenhouse gases are accumulating, many aspects of the problem are uncertain, and learning about that uncertainty is occurring over time. The existence of learning and uncertainty essentially translates the problem into one of valuing information received over time. Furthermore, the fact that one is learning about an uncertain process has implications for the optimal control of emissions today. There is a tradeoff between acting now to control greenhouse gas emissions vs. delaying control when faced with uncertainty coupled with learning.

The work begins with a version of Nordhaus' DICE model that the PI has used for integrated assessment of CO₂ policies (Kolstad, 1993). The specific objectives of the proposed work are a) to enhance the representation of climate uncertainty in the existing integrated assessment model, focusing on damage uncertainty, control cost uncertainty and climate sensitivity uncertainty; b) to recast the existing stochastic programming integrated assessment model as an infinite horizon dynamic program; c) to further develop the use of Chebyshev approximations to solve the DP ; and d) to develop policy implications from the integrated assessment model, parameterized by learning.

Products: (1) A detailed understanding of learning in integrated assessment models of climate change; (2) Reinterpretation of integrated assessment models within the DP framework; (3) Improved methods for solving stochastic DP problems in the context of integrated assessment models; (4) New policy implications for climate change policy vis-a-vis learning and uncertainty.

Approach: The core of the research approach is in efficiently solving dynamic programs with four to eight states. In addition, research involves interpreting models of learning and

integrated assessment models within the framework of dynamic programming.

The three tasks for implementing this are (1) compare methods for simple one-state DP; (2) extend promising methods to multi-state DP; and (3) implementation of integrated assessment model with learning. Although these tasks are naturally somewhat sequential, we plan to progress on all three fronts simultaneously, with some emphasis on task 1 initially.

The first task involves comparing methods of solving simple one-state dynamic programs. This task involves implementing a variety of numerical methods for solving DP's, and then applying these methods to a simple one-state DP, such as the standard optimal growth model with homogeneous capital. This approach should provide vital performance information, necessary before moving to more complex multi-state problems. Candidate numerical methods are the several methods of Judd (minimum weighted residuals applied to the policy and value function), neural network approaches, variants of the Judd method, the functional iteration method of Stokey and Lucas, and methods involving nonlinear complementarity.

The second task involves selecting the best solution technique identified in Task 1 and developing an algorithm for solving the multi-state DP, with the number of states ranging up to eight (if possible). This algorithm will be used directly in the integrated assessment model.

The third task involves implementing the integrated assessment model within the DP solver developed in Task 2. This involves the standard computational issues but also a significant amount of data development, particularly regarding uncertainty and the learning process.

Results to Date: Because of contracting delays, the project has only been underway for a short time. Nevertheless, some results have begun to emerge. In fact, we are very pleased with the results we have obtained to date. We are very optimistic that the project is on the right track

and that significant results will emerge in the coming year. Progress is in three areas.

We have successfully converted the PI's stochastic programming integrated assessment model to solution as a dynamic program, using a neural network approach. This work has yet to be documented but we expect to do so over the next few months. Although the approach is considerably slower than conventional solution methods, advantages are that the time horizon is infinite and the structure is considerably more flexible. This is a major breakthrough in that no other integrated assessment models are solved as DP's, primarily because of computational problems.

We have also been participating in the Stanford Energy Modeling Forum's study group on uncertainty in integrated assessment models. This should provide additional insight into comparative performance of our methods with

those of other investigators. This is not a major aspect of the project but allows for a measure of validation of our approach in that we are comparing our results with those of others.

Perhaps the most interesting result that has emerged to date is our focusing on Bayesian learning about temperature. We are trying to capture the phenomenon that one may not know that the climate has changed until it is too late. This is represented by stochastic forcing within the integrated assessment model and the economic agent learning about damage by observing the stochastic realizations of damage. We have not yet been able to solve this problem but are making good progress.

Publications: None to date.

Student and postdoc participation: Aran Ratcliffe (25%), David Kelly (10%)

The Effect of Atmospheric Aerosols on Optical and Radiative Transfer Properties of the Atmosphere

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Objectives: There are three main objectives for this project, each relating to the overall goal of developing an accurate description of how atmospheric aerosols affect the radiation balance in the atmosphere:

1. Characterize Atmospheric Aerosols and Solar Radiation: Collect an experimental data base that characterizes atmospheric aerosols, ambient weather conditions, and resulting solar radiation over several seasons in a midwestern rural area.

2. Validate Radiative Transfer Models: Utilize the data base to verify existing theoretical and semiempirical models of aerosol particle size, water content, refractive index, light extinction (scattering and absorption), and atmospheric radiative transfer. The validated models will be used to explore the link between the chemical and physical characteristics of the aerosol and

optical properties of the atmosphere.

3. Develop Numerical Representation of Midwestern Aerosol Characteristics: Use the measured data set to develop numerical descriptions of measured size distributions, aerosol refractive index, and the species' contribution to atmospheric extinction. These descriptions will indicate typical properties of midwestern aerosol particles.

Products: The radiative effects of atmospheric aerosol are likely to play an important role in global climate change. This project will produce results relevant to the global change research effort, specifically:

1. Important optical properties of the atmospheric aerosol in midwestern rural locations will be measured. These properties include the

chemical composition, size distribution, and scattering coefficient. Surface irradiance will also be measured.

2. The components of the extinction coefficient and the mass efficiencies of scattering, absorption, and extinction will be calculated for the aerosol components. The refractive index of the aerosol will be calculated, and the size distribution will be described numerically. The surface irradiance will be calculated with a radiative transfer model.

3. Reliable values and models for size distribution, water content, and refractive index of the aerosols characteristic of midwestern rural locations will be determined.

4. Atmospheric aerosol models and models of light extinction and radiative transfer will be evaluated using measured data.

5. The data base will be an important resource for future theoretical studies and modeling efforts.

Approach: An extensive field campaign was set up and conducted to measure the size distribution and chemical composition of major particulate aerosol species over four seasons at a midlatitude, midcontinental site. These measurements are important in order to determine the effect that aerosol particles have on atmospheric radiative transfer and climate.

Several instruments were used to collect size segregated samples of the aerosol particulate matter. An eight-stage MOUDI impactor was used to collect samples for analysis of sulfate and nitrate ions. A high volume PM-10 sampler, equipped with an impactor, yielded samples for analysis of elemental carbon (soot), organic carbon, ions, and metals. Impactor data were fit to bimodal, lognormal curves for use in optical models. Several dichotomous samplers gave information on elemental and organic carbon, ions, and metals in two size ranges: between 10 μm and 2.5 μm and less than 2.5 μm . The combined analysis of the samples allowed quantification of the size distribution of the major aerosol species: sulfate, nitrates, elemental carbon, organic carbon, and metals.

Two direct reading instruments were used for measurement of the aerosol scattering coefficient and the size distribution. The scattering

coefficient was measured with a nephelometer. An optical particle counter (OPC) recorded size distribution information. The size distribution data from the OPC were also reduced to a bimodal, lognormal fit for future use in optical models. Because the Bondville site is also used by the Illinois Climate network, data on meteorology were also available. These data included wind speed and direction, temperature, relative humidity, and solar radiation.

Two types of sampling formed the basis of the year long program: intensive and standard. Intensive sampling involved consecutive samples of 24-48 hours for a period of one week. In standard sampling periods, 24-48 hour samples were taken, overlapping with the EPA sampling schedule, in which every sixth day is a sampling day. With these two types of sampling, we have 30 sample periods, spanning the four seasons of 1994.

Additional aerosol and radiation measurements will be made at Urbana, Illinois during the summer of 1995 as part of a study to determine to what extent aerosol particles directly reduce the amount of solar radiation reaching the surface of our site. As part of this determination, we will validate a Multi-Layer Radiative Convective Model (MLRCM; Oh, 1989). The model validation will be made by comparing ground radiometric measurements with model predictions for the net local downward radiation flux, calculated using measured aerosol parameters. The aerosol and radiative measurements will be made at the Urbana Wind and Atmospheric Site (UWAS), a different field site from the 1994 Bondville site measurements. This is because of the lack of facilities at Bondville to measure properties of the upper atmospheric aerosol. The upper atmospheric and stratospheric aerosol characteristics are needed for the model validation and will be provided by University of Illinois Wind and Temperature LIDAR (Light Detection and Ranging) system at UWAS. Temperature and relative humidity profiles are also needed and will be provided by the National Weather Service - Upper Air Site (NWS-UAS) located 65 miles west of Urbana at Lincoln, IL. After validation, the model will be used to investigate the effects of aerosols on local radiative transfer by systematically varying aerosol parameters.

Results to Date: Measurements of the physical and optical properties of atmospheric aerosols

were made during 24 and 48 hour sampling periods at Bondville, IL. A total of 30 measurement periods covered the spring, summer, fall, and winter seasons in 1994, effectively characterizing the aerosol properties for this rural, midcontinental, midlatitude site. The particulate concentration at the Bondville site is typically below $50 \mu\text{g}/\text{m}^3$ and concentrations of sulfate (assumed in the form of ammonium sulfate) and organic carbon dominate.

Our study of aerosol optical properties focused on determining the aerosol scattering coefficient and species efficiencies using measured aerosol properties and an aerosol model. The Elastic Light Scattering Interactive Efficiency (ELSIE; Sloane, 1986) model was used. It is semi-empirical and uses the relative humidity with the size distribution of sulfate, nitrate, elemental and organic carbon, and the residue to calculate the amount of water associated with the aerosol. (Residue is the term used to describe material identified gravimetrically, but not chemically.) ELSIE then uses Mie theory for layered spheres to calculate scattering and absorption coefficients and efficiencies.

We used ELSIE to calculate the particulate scattering and absorption coefficients and efficiencies for a range of wavelengths. The wavelength-dependent coefficients are a measure of the amount of light scattered or absorbed by the aerosol particles and will be used in future radiative transfer modeling. The efficiencies are an important parameterization for climate models as they relate the expected change of light scattering or absorption to a change in aerosol loading in the atmosphere. Because of the importance of the ELSIE predictions, it is crucial that this model be validated.

We validated ELSIE by comparing the scattering coefficient calculated at 550 nm to that measured at the same wavelength by the nephelometer. Our comparison was based on the measured and modeled scattering coefficient for 30 measurement periods made in the spring, summer, fall, and winter months of 1994. Our validation shows that the ELSIE model is accurate to within 28% for the measurements made at Bondville, IL. Other investigators have reported better accuracies of this model - 10% (Sloane, 1986) and 25% (Lowenthal et al., 1994). Excluding one outlying point, our accuracies are 22% and within acceptable ranges.

Once validated, the ELSIE model could be used with confidence to determine the relative contributions of each of the species to the predicted particulate scattering coefficient as a function of Julian Date (JD). Aerosols containing high concentrations of sulfate ions (modeled as ammonium sulfate) and organic carbon were found to have the highest scattering coefficient. This analysis also shows the variation of the scattering coefficient at Bondville over the seasons. The spring (JD 128-169) and winter months (JD 301-340) have the lowest scattering coefficients, while the highest scattering coefficients are realized during the summer (JD 194-244) and fall (JD 250-295) months.

We also investigated the relative percentage contribution to the scattering coefficient under separate low, high and mid ranges of relative humidity. Sulfate species have the highest contribution in the high relative humidity range, due to their characteristic growth at relative humidities above 80%. At lower relative humidities, the organic carbon species contribution to the scattering coefficient was found to be comparable to the sulfate contribution. In all cases, the contribution by nitrate species was much lower than the sulfate and organic carbon contribution. The elemental carbon contribution was the lowest of all species despite the fact that the elemental carbon species are mostly present in the very fine size range (less than $0.4 \mu\text{m}$ in diameter). The low contributions of the elemental carbon are because of the very low concentrations of this species (less than $0.5 \mu\text{g}/\text{m}^3$) in the aerosol measured at Bondville.

The single scattering albedo, ω , is the ratio of the scattering to extinction coefficient. It tends to one for the no-absorption case and to zero for the no-scattering case and is important in determining the effect of aerosols on radiative transfer. For example, the value of ω can determine whether direct aerosol forcing results in cooling or warming. Because both cooling and warming exist over the range of possible ω values, there exists a value ω_{critical} such that if $\omega < \omega_{\text{critical}}$, the direct aerosol effects result in heating and if $\omega > \omega_{\text{critical}}$ then the direct aerosol effects result in cooling. This critical value is estimated to be between 0.7 and 0.9 (Bohren and Huffman, 1983), and Hansen et al. (1980) give $\omega_{\text{critical}} = 0.85$. In most cases the single scattering albedo is so high as to preclude any heating effects.

We evaluated our determinations of the single scattering albedo ($N=30$) at a wavelength of 550 nm as a function of the average relative humidity over periods of 24 or 48 hours. The analysis shows that there are only five of our sample periods for which $\omega < \omega_{\text{critical}}$ (indicating warming). All days on which this was observed corresponded with days during which the average recorded relative humidity was less than 60%. Therefore the typical direct effect of the Bondville aerosol would be cooling.

Most of the variation in the single scattering albedo with relative humidity is due to the variations in the scattering coefficient. The absorption coefficient measured at Bondville is approximately one tenth of the scattering coefficient and does not vary very much.

The mass scattering efficiency of species i is defined as the ratio of an incremental change in mass of species i to the accompanying change in the scattering coefficient. The absorption and extinction efficiencies are similarly defined. We determined the scattering, absorption and extinction efficiencies for the Bondville aerosol using the ELSIE model and measured size distributions and concentrations of the sulfate, organic carbon, nitrate and elemental carbon aerosol, and the prevailing relative humidity conditions.

Another research focus was the mass scattering efficiency for one of the most important species (sulfate) as a function of relative humidity. The sulfate scattering efficiency is independent of relative humidity at low relative humidity and increases rapidly at relative humidities above 70%, due to the characteristic humidity growth of sulfate aerosols at these humidities.

In summary, aerosol optical properties at ground level have been characterized over the course of a year. In the future, our measurements will be expanded and used to validate and explore the predictions of a radiative transfer model. The core of our future work involves determining to what extent aerosol particles directly effect the amount of local downwelling radiation in a rural, midwestern site. As part of this determination we will also validate the Multi-Layer Radiative Convective Model (MLRCM; Oh, 1989). These objectives will be achieved through a combination of the use of MLRCM and field measurements. The future research will be an important contribution to the use of MLRCM in

investigations of the effects of aerosols on radiative transfer.

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Presentations:

"The Effect of Aerosols on Radiative Transfer at a Rural Site," S.M. Larson, University of Vienna, Institute for Experimental Physics, Vienna, Austria, June, 1994.

"Comparison of Measured and Modeled Light Scattering Coefficients and Estimation of Mass Scattering Efficiencies at a Rural Illinois Site," A.H. Omar, S.M. Larson, S. Biegalski, S. Landsberger, D. Dolske. Accepted for presentation at the 1995 Annual Meeting of the American Association for Aerosol Research.

"Light Absorption by Atmospheric Particles at a Rural Midwestern Site," Stacy B. Mann, S. Biegalski, S.M. Larson, S. Landsberger, D. Dolske. Accepted for presentation at the 1995 Annual Meeting of the American Association for

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"Size Distributions of Rural Atmospheric Aerosol Particles," S. Biegalski, A.H. Omar, S. Larson, S. Landsberger, D. Dolske. Accepted for presentation at the 1995 Annual Meeting of the American Association for Aerosol Research.

Other Products: Master's thesis for Stacy Mann, Ph.D. thesis for Ali H. Omar, independent study projects for Steven Biegalski, Amy Groteleuschen, and Scott Hummel.

Student Participation: Ali H. Omar 50%, Steven Biegalski 50%, Stacy Mann 25%, Amy Groteleuschen 10%, Scott Hummel 10%.

Amazonian Deforestation, Succession, and Carbon Cycling III: A GIS/Spectral Multitemporal Analytical Approach

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Objectives: The primary objective of this research was to identify land use and land cover changes along the Transamazon Highway west of Altamira, Brazil from 1985-1991 using multi-temporal Landsat TM data informed by detailed 1992 - 1993 field observations and measurements. These data identifying changes will be in a form possible to integrate with other physical and cultural parameters in the study area to assess rates of vegetation succession and factors responsible for those rates. Two secondary objectives are addressed to strengthen the new methods developed and to begin to develop data bases for integration into future modeling of these environments with respect to aspects of carbon cycling. Specifically, the remote sensing methods developed in this research were applied and tested in Amazonia estuary sites (i.e. Marajo Island) as well as the primary Transamazon Highway sites west of Altamira. Also, a remote sensing-based (TM) soil order map of part of the Altamira study area was developed.

Products: Land use and land cover maps of nine classes of features including three stages of succession and moist mature forest were developed from the Altamira study area for 1985, 1988, and 1991. Successfully delineation of successional stages of humid tropical forests using computer analyzed Landsat TM data was not noted in the literature until research results from this project were published in major journals. Land use and land cover change patterns were derived from analysis of the three data sets with particular emphasis accorded to

successional vegetation and the rates at which they progress back to moist mature forest. This product showed the spatial patterns of successional changes as well as the speed or rate of change. These multitemporal land use/land cover patterns and the rates of changes that can be derived from them will be associated and modeled with other physical and cultural parameters in the area in the future to derive hypotheses about mechanisms of vegetation dynamics.

An important, but secondary product developed by personnel conducting researching in this project is a single date analysis of botanical features/vegetation classes in estuarine areas of the Amazon. This aspect of the project research supported the validity of the methods developed and implemented to identify successional forest and other difficult to delineate features in the Amazon using computer-analyzed TM data heavily supported by ground-based observations.

The final secondary product developed was a soil order map covering significant parts of the Altamira study area. Development of this map utilized the effects of the 1985 drought which exposed soil in almost 30% of the area (primarily pasture and crops). Special remote sensing techniques were applied to highlight soils in a predominantly bare condition, but containing appreciable amounts of sparse green and yellow (dead) vegetation cover in selected areas where shallow rooted plants were most affected by drought.

Approaches: Three date Landsat TM data (1985, 1988, 1991) were analyzed using unsupervised/clustering and supervised (a hybrid maximum likelihood/texture-based algorithm) approaches to derive a classification of nine , primarily vegetation , features focused on a 5,500 km sq study area west of Altamira. An independent classification of Marajo Island (Amazon estuary area) used the techniques developed and implemented in the Altamira study area was conducted to help verify the validity of methods developed. In some of the analyses principal component transformed and ratio transformed TM data were used to enhance classification results. In one approach each one of the three dates were classified individually and in an alternate approach all the dates were combined and classified collectively. In both cases there was intensive use of current and historical field data that was collected during 1992 and 1993. Separability or divergence programs were used extensively to help assure that representative training statistics were developed for supervised classification. Test fields to verify classification accuracy were developed by selecting sample plots of known character in the field during 1992 and 1993. During 1993, GPS was used to help assure good locational accuracy of test plots. The test plots were classified to provide insights into accuracy of classifications. Error matrices and kappa statistics were calculated.

Geographic information system overlay approaches were used to analyze the three individual classifications to identify change patterns that focused on rates of vegetation succession. Change detection using the three TM data sets was also accomplished through registering and atmospherically correcting the three data sets and conducting an analysis in which each multitemporal spectral signature developed though high dimensional clustering represented a three date change condition. This multitemporal cluster/supervised classification approach requires a high level of remote sensing expertise.

Additional data sets (soils, topography, distance from road, etc.) need to be integrated in a GIS with classification data to model or in other ways provide insight into successional processes, but such work has just begun and requires additional support to be completed.

A separate analysis of soil orders was conducted

using 1985 TM data, a time when shallow rooted vegetation in the Altamira area was highly stressed due to drought resulting in unusually large areas of bare or partially bare soils. Specialized transformations of TM data were implemented to classify soil orders (approximately 30% of the area). The Fukuhara index, which can subtract the effect of green vegetation in soils with sparse vegetation cover, was used along with other ratios and principal component transformed data to identify the soil order (oxisol, alfisol, ultisol) in these partially vegetated or bare soil areas. These data combined with other information could be developed into a full area soil order map (1:50,000 or 1:100,000 scale) that would become one of the GIS files integrated with classified data to help understand forest succession rates and processes.

Results to Date: Classification of nine features including three stages of forest succession, moist mature forest, and pasture was successfully achieved with a test field accuracy of 88 to 98 percent (overall accuracy 94 percent) for three individual dates of TM data in the study area when the texture-based maximum likelihood approach to classification was implemented. The use of standard per pixel maximum likelihood classification gave results typically in the 71-77 percent accuracy range for the features of interest. In general it was found that for some classes no improvement or a minor improvement of 1-2% in accuracy for other classes was achieved using these transformed data sets, thus for this research the use of original untransformed data is suggested for efficiency in developing information. The use of transformed data did improve classification results in a few subareas , but this improvement was not sufficiently great to warrant its implementation on a large scale. Classification results for the Marajo Island area, which included some classes different from Altamira, was equally successful using the methods employed.

The GIS analysis which combined the three individual classifications produced a land use/land cover change map that provided insights into rates of vegetation succession. The multitemporal cluster/ supervised classification approach generated a slightly more accurate product with fewer small meaningless change classes, but it is more difficult to implement than using three independent classifications overlaid in a GIS. The change patterns identified using

either approach are in preliminary stages of interpretation, but a few hypothesis have been developed from this analysis. For example many of the changes regions identified as experiencing rapid succession are in high quality alfisol soil areas and/or are in particularly well-watered areas (small floodplains/ depressions) while conversely areas with very slow succession are in oxisols areas often in well drained/dry sites. This change map is the prime product from this research and requires intensive additional research. Future work should focus on assessing succession processes and dynamics.

Soil information derived from TM analysis of the unusually dry 1985 date was used to begin to develop a soils data base, which when used in combination with a digital elevation model, and other parameters derived in the field or extracted from TM classifications will help provide a basis for modeling and assessment of selected vegetation succession processes and dynamics. The accuracy of soil order identification using TM data during the 1985 drought year averaged approximately 75 percent which represents good results for such a preliminary analysis.

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Student Participation: Yinghong Li 33%; You Wu 33%; Eduardo Brondizio 50%; David Smith 20%

Development and Demonstration of the Uses of Multivariate Outputs in Integrated Climate Assessment Models

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Objectives: Most climate impact assessment models produce a single output, typically measured in terms of dollar losses. As a consequence they do not display the rich economic, social, and ecological variety that is likely to characterize actual impacts. This is a problem because many different policy actors are involved in climate related policy decisions, and each is likely to assign different degrees of importance to different impact categories and reach very different conclusions about how a given vector of impacts should be valued. Models which integrate across all the separate impact categories and affected parties are likely to be of limited use in exploring climate change policy questions, since they will not be able to differentiate and support the different needs of various actors.

These considerations suggest that there is a need to develop techniques for integrated impact assessment that produce and use multivariate outputs. We are developing, demonstrating, and evaluating such techniques in the context of the Carnegie Mellon ICAM-2 framework. Multivariate outputs can be used in several ways. Single outputs or simple combinations of outputs can be used to evaluate alternative policy options against specific dimensions. The entire vector of outputs can be used, either directly, or through a utility function, to allow users to make holistic judgments. In addition, multivariate outputs can be used to work backwards to estimate the implicit cost of adopting certain "inviolable constraints".

Through a combination of such techniques, we are exploring the different valuations of specific scenarios for different key actors. This is the first step toward identifying "tradeoffs" that might be made among groups of actors who must cooperate if a particular strategy is to succeed.

Products: 1) A parametric analysis using simple constructed utility functions which reflect the values of key actors and demonstrate the usefulness of the approach (completed). 2) A detailed research plan to obtain utility functions from a number of groups of real policy actors in

the U.S. and around the world, suitable for use in integrated assessment studies.

Approach: To illustrate the usefulness of the approach we constructed multi-attribute utility functions for two representative actors from the industrialized world - a pro-environment actor ("Environmentalism"), and a pro-growth actor ("Industrialism"). Subjective preferences were defined for the two actors over four climate change metrics - global mean temperature change, global mean sea level rise, changes in income from climate change and abatement measures, and changes in ecosystem prevalence. The Environmentalism was assumed to be risk averse to changes in ecosystems, sea level and global mean temperature, and risk neutral to changes in income. In contrast, the Industrialism had qualitatively opposite preferences. The single attribute utility functions for the metrics were combined additively, where the different actors associate different importance weights to each of the attributes.

The resulting multi-attribute utility function was used to evaluate three greenhouse policy options: a do-nothing option (A), a low carbon tax option (B) and a high carbon tax option (C). The two actors had very different choices for dominant policy strategies. Environmentalists preferred option C in most situations, except in the very short term where they are indifferent (B~C) between the two tax options. Industrialists on the other hand preferred option A in most cases, except when the decision rule is to minimize worst case outcomes in the long term where option B is preferred. The decisions of the two actors are most similar when either the short term expected damages or chances of long term low probability-high consequences events are minimized. These results demonstrate the usefulness of performing multi attribute evaluations of climate change policy options. Details of the work can be seen in Kandlikar and Morgan (1995).

The follow-up to the above analysis is a value construction research plan and protocol. This plan will be used to obtain utility functions from

a number of groups of real policy actors in the U.S. and around the world. An important aspect of this approach is that it places climate change squarely in the context of overall global change. A generic value tree with the flexibility of representing the values of various actors is constructed. The end points of the value tree also called the "leaves" correspond to socio-economic and environmental variables that individuals care about. Many of the leaves will be affected by climate change, some may not be affected by climate change, others may be affected but in ways that are hard to quantify. For each of the leaves affected by climate change a single attribute utility function is elicited. As a starting point for the analysis we assume only incremental changes in the attributes a reasonable assumption as long as climate change does not cause major perturbations in the global economic and social landscape.

There are two dimensions to the value construction exercise. The first is a geographical dimension. Individuals may feel differently about climate change which has effects on their own community and other which are *socially* close to them. They may also feel differently about ecological impacts in different locations. Additionally, individuals may value ecosystems on the basis of their ecological prominence and richness rather than a geographical basis. A set of map based response forms are being developed to address these issues. The second dimension is temporal. As one moves further into the future, the line between generations starts to get blurred. We expect people to draw cleaner distinctions between impacts to those who they feel close socially close, and those who are more distant, for the next few generations that they do for later generations.

The value construction protocol is based on the notion that individuals have well characterized basic values. It is assumed that they may understand tradeoffs and have robust value judgments at a higher level, they may not have well articulated values on all parts of the tree, and may have to construct their values (rather than have them elicited). We are working to develop methods that will allow respondents to work from the top-down and from the bottom up in the tree, in order to construct their multi-attribute utility function.

Once we have completed our development of a

utility construction method we will run a series of experimental studies to empirically evaluate the approach. If after refinement, we conclude that the approach is feasible, in the future we will seek support to ask several groups in the US and elsewhere to construct utility functions for use in integrated assessment studies.

In addition to the value construction exercise we are also working on methods to display multiple impact metrics. For the specific case of the climate problem, we are developing and demonstrating a variety of options including: Displays that summarize all outputs simultaneously; Displays that combine subsets of attributes (through functional combinations and/or parameterizations); A simple system that will allow us to specify multi-attribute utility functions for different actors and display the results as one-dimensional measures of utility.

Results to Date: We have completed the parametric analysis using simple constructed utility functions. The work was presented at the First Open Meeting of the Human Dimensions of Global Change Community at Duke University and has been accepted for publication in *Human Dimensions Quarterly*. We are now developing the value construction protocol which forms the core of the second stage of the work.

Manuscripts in preparation: Kandlikar, M., M. Granger Morgan (1995), Addressing the Human Dimensions of Climate Change: A Multi-Actor, Multiple Metric Approach, *Human Dimensions Quarterly*, in press.

Presentations: Kandlikar, Milind (1995) A Multi Attribute Approach to Climate Change Policy, Seminar at CMU, May 1995.

Kandlikar, Milind.(1995a) A Multi-Attribute Framework for Climate Change Policy Analysis. First Open Meeting of the Human Dimensions of Global Change Community, Duke Univ, Durham, N.C., June 1995.

Student participation: In addition to Milind Kandlikar, the post doctoral fellow who has taken the lead on this work, a number of current Ph.D. students in the integrated climate change group at CMU have participated in the discussions and intellectual debate that has led to the formulation of the second stage of this research. They include Elena Shewliakowa, Charles Linville, Natesan Mahasenan and Matt Oravetz.

Trace Gas Fluxes (N_2O , CH_4 , CO_2) in Agricultural Ecosystems: Biospheric Feedbacks

G. P. Robertson and K. Paustian
Michigan State University

Objectives: The overall objective of this project is to provide a more complete understanding of the role that row-crop agriculture plays in the production of radiatively active trace gases. Specific objectives are 1) to examine the predictability of short-term changes in N_2O production and CH_4 uptake in different cropping systems and determine whether these fluxes integrate to regionally significant values; 2) to examine the extent to which CO_2 fluxes from agricultural soils are related to soil N-status and the size of the active fraction of soil organic matter (SOM), and 3) to examine the causal factors regulating the temporal dynamics of CH_4 and N_2O fluxes in agricultural systems. We are using this information to further develop, parameterize, and validate mechanistic models of these trace gas fluxes from agricultural soils.

Products: An evaluation of the hypotheses that ecosystem disturbance associated with normal agricultural practices leads to (1) elevated N_2O vis à vis fluxes from undisturbed native habitats, (2) disruption of the soil's natural capacity for methane uptake, and (3) a greater proportion of decomposition products partitioned to CO_2 rather than labile soil organic matter.

Approach: Our general approach has three major components: 1) extensive measurements of fluxes in a series of crop and native communities representative of major row crop systems (corn-soybean-wheat rotations in conventional tillage, no-tillage, and low chemical input tillage systems) vs. fluxes in adjacent never-tilled communities in native vegetation; 2) intensive measurements of fluxes in row-crop communities; and 3) parameterization of existing biogeochemical models to allow prediction of fluxes in response to long-term management. Extensive measurements are based on weekly to biweekly samplings in large replicated field plots and native communities within the KBS Long-Term Ecological Research site. Intensive measurements are based on a near-continuous in situ trace flux measurement system developed for this study.

Results to Date: Results suggest a large

historical effect of cultivation on both N_2O and CH_4 fluxes. As shown in Figure 1, methane uptake is severely depressed in cultivated treatments relative to rates in forested, never-tilled sites on the same soil series. Based on patterns in successional vs. old-growth sites, as well as on fertilizer treatment effects, this flux change appears to be independent of fertilizer-N application and instead related to an historical effect of cultivation itself. In contrast to CH_4 fluxes that show a depression of flux rates under cultivation, N_2O fluxes appear to increase along this gradient, again more in response to cultivation itself than in response to fertilizer application. This suggests that global budgets for N_2O -N, usually constructed on the basis of some fraction of fertilizer-N converted to N_2O , are underrepresenting the impact of agriculture on global N_2O fluxes. Measurements of fluxes in replicated fields suggest that N_2O production is 50-100% higher in cultivated systems than in adjacent native vegetation.

Further laboratory experiments to identify controls on CH_4 uptake show that uptake is sensitive to soil moisture but within the agricultural communities relatively insensitive to soil nitrogen. Results from our intensive flux measurement system show high temporal variability for N_2O and CH_4 fluxes, with fluxes varying by up to 100% within the same day. Over a typical 2-day period in July 1994, for example, the N_2O flux doubled for a 6 hour period and then returned to initial rates; CO_2 (soil respiration) fluxes over this period remained relatively constant. This variability appears to be an important missing consideration in the construction of local N_2O flux budgets for agricultural systems.

Manuscripts published and submitted:

Paustian, K., G. P. Robertson, and E. T. Elliott. 1995. Management impacts on carbon storage and gas fluxes (CO_2 , CH_4) in mid-latitude cropland ecosystems. *Advances in Soil Science*, in press.

Smith, K. A., G. P. Robertson, and J. M. Melillo.

1994. Exchange of trace gases between the terrestrial biosphere and the atmosphere in the mid-latitudes. Pages 179-204 in R. Prinn, editor. *Global Atmospheric-Biospheric Chemistry*, Plenum Press, New York, USA.

Robertson, G. P. and K. L. Gross. 1994. Assessing the heterogeneity of belowground resources: quantifying pattern and scale. Pages 237-253 in M. Caldwell and R. Percy, editors. *Plant Exploitation of Environmental Heterogeneity*. Academic Press, New York, New York USA.

Klingensmith, K. M. and G. P. Robertson. Nitrous oxide emissions from a row crop ecosystem of the U.S. Midwest. Submitted to *Biogeochemistry*.

Robertson, G. P., W. L. Reed, and S. J. Halstead. Attenuation of atmospheric methane uptake in agricultural ecosystems. Submitted to *J. Geophys. Research*.

Robertson, G.P. and W.L. Reed. Methane uptake in an agricultural soil: response to moisture. Submitted to *Soil Biology and Biochemistry*.

Presentations 1993-94:

The impact of soil and crop management practices on soil spatial heterogeneity. (G. P. Robertson) International Symposium on Soil Biota Management in Sustainable Farming Systems, Adelaide, Australia 1994.

The historical impact of cultivation on trace gas fluxes. (G.P. Robertson, S.J. Halstead). Ecological Society of America, Snowbird, UT, August 1995. *Ecol. Soc. Amer. Bull. Suppl.* 76: 5.

The functional significance of denitrifier population diversity to nitrous oxide production in terrestrial ecosystems (M. Cavigelli, G.P. Robertson). Soil Ecology Society, Ft. Collins, CO, April 1995.

Functional diversity of denitrifiers in soil (M. Cavigelli, G.P. Robertson). Ecological Society of America, Snowbird, UT. *Ecol. Soc. Amer. Bull.* 76: 42.

Student participation: Gina Zuniga, State University of New York, 25%; Chikweita Settle, Kellogg Community College, 25%; Susan Bovee, University of North Carolina, 25%; Jarrod Fiengo, Kalamazoo College, 25%; Amanda Yager,

Michigan State University, 25%; Michel Cavigelli, Michigan State University, Ph.D., 10%; Timothy Bergsma, Michigan State University, Ph.D., 25%; Per Ambus, Michigan State University, post-doctoral, 100%.

Figure 1. Methane uptake in Treatment 1 (high input corn-soybean-wheat) [top], Treatment 8 (never-tilled native vegetation) [middle], and the deciduous forest site [bottom] on different 1994 sample dates. Each bar represents 4 replicate sites.

An Integrated Assessment of the Economic, Ecologic, and Energy Demand Impacts of Global Climate Change on the Great Lakes Basin: II

Barry M. Rubin and Clinton V. Oster, Jr.
Indiana University

Objective: The research goals are to: (1) develop and test a methodology for undertaking an integrated assessment of the multi-state regional economic impacts of global climate change, which can be adapted for use in other multi-state regions; (2) identify the specific economic and energy demand impacts of and potential adaptations to global climate change for the Great Lakes region; and (3) provide a framework for developing and evaluating public policy designed to mitigate the negative effects of regional climate change under alternative forecasts of the extent and rate of global climate change.

Product: The construction and application of an integrated economic-environmental-energy demand econometric model enables the regional effects of global climate change in the Great Lakes Basin to be examined for a broad range of economic indicators, resulting in the following outcomes:

- the development of a prototypic methodology and modeling framework which can be cost-effectively utilized for integrated assessment of regional economic and energy demand impacts of global climate change, and which can be adapted for use in other regions or for examining other types of large-scale environmental changes;
- a major expansion of knowledge of environmental-economic-energy demand interactions resulting from climate change through intensive study of regional impacts, and identification of these interactions and impacts for the Midwestern Great Lakes Basin;
- a significant improvement in the ability to predict the regional impacts and economic consequences of global climate change;
- the integration of economic, demographic, environmental, energy demand, and climate impacts into one model structure;
- the development of a framework for

developing and evaluating mitigation and adaptation strategies under alternative forecasts of the extent and rate of climate change.

Results of this research will aid in the development of effective adaptation policies, leading to improved management of natural resources such as Great Lakes fisheries. By identifying the economic consequences of global climate change for this region, the research will inform the public policy debate on climate change strategies. The research will also provide a significant improvement in the ability to predict regional impacts. The final product will be a prototypic methodology and modeling framework that can be cost-effectively implemented, and a set of mitigation and adaptation strategies that have been subjected to the rigorous policy analysis provided by the model.

Approach: The original proposal for this project was based on a two-year project plan. There is no change in the overall scope of this research effort from that originally specified. The primary focus of the *first year* of the project was described to include data collection, refining the theoretical framework for the model, establishing preliminary specifications for the econometric equations, estimating the core equations of the model, and conducting an initial analysis of the pressures for change in the economic system. As of July 1995, an initial version of the full model had been constructed and testing and tuning of the economic and ecologic components was underway. The *second year* of the research will be devoted to extending, refining, and finalizing the model; examining the character of the forces for change in the economic system; developing the most likely adaptations of the economic system in response to these forces; developing alternative mitigation and adaptation strategies; and comparing the impacts of these alternative strategies in the context of policy analysis.

The tasks for the first year were broken down

into four basic stages: data collection; initial specification of equations representing specific economic variables (e.g., state employment in agriculture, gross state product); aggregation of individual equations into and fine tuning of the simultaneous equation model; and forecasting. Using a baseline forecast and a climate change-scenario forecast, the resulting climate change impacts for the period from 1995 to 2010 can be derived. In order to derive the baseline forecast, it is assumed that the model's non-climate exogenous variables would continue to change based on past trends. In order to project these trends through 2010, an autoregressive time-series forecast approach provided by the SAS software FORECAST Procedure is utilized. The values of the climate variables are projected as remaining relatively constant over the forecast period. To derive the climate-change scenario, the climate variables are assumed to have an exponential growth rate consistent with doubling the concentration of carbon dioxide in the atmosphere within ten years, and then continuing to grow at an accelerating rate for the remaining years thereafter. This climate-change scenario is intended to illustrate what would occur *if the global warming likely during the next 50 to 75 years took place over the next 20 years*. This 20 year forecast allows the effects of global climate change to be explored in terms relevant to current economic conditions.

Results to Date: The Great Lakes basin, consisting of Illinois, Indiana, Michigan, Wisconsin, and Ohio, is the area of study for this project. This region encompasses one tenth of US land area, one fifth of US population, and leads the country in key economic sectors, including agriculture and manufacturing. The region has fertile soils, abundant northern forests, moderate temperatures, plentiful rainfall, and inexpensive transportation. However, the rich water resources in the Great Lakes (containing 18% of the world's and 95% of the nation's fresh water) are severely threatened by global climate change and the potential redistribution of water resources.

The model structure and the regression estimation results for the primary stochastic equations of the model have been completed. The model is now in its final tuning stage. All independent variables included in these equations are statistically significant at the 0.10 level or better. Thirteen employment sectors have been empirically modeled with employment

and wage equations: farming; construction; manufacturing; services; finance, insurance and real estate; retail and wholesale trade; transportation and utilities; federal and state and local government; mining; and forestry and fisheries. The specification of these equations commonly follows the generalized formulation of employment equations in previous research, with the major non-climate explanatory variables being regional wages in the respective sector, national demand as represented via GNP, and local demand as represented by population, total employment, or employment in related sectors. The climate variables in these equations include daily mean annual precipitation, winter precipitation, spring precipitation, and summer precipitation, mean daily annual and winter temperature, and various soil stress indices. In addition to these employment sectors, equations were developed for government revenue and expenditures, total energy consumption, forest use, gross state product, state unemployment rate, personal income, population, and net migration to capture the impacts of climate change on these variables.

Dummy variables were used for each of the states so that the aggregated Great Lakes model could be used for any of the individual states by "turning off" the dummy variables for all but the state of interest. In addition, interaction variables were employed to capture the strong impacts any one state might have on the dependent variable of an equation. As a result, the information presented proxies the environmental-economic linkages in a state's economy as they exist within the larger Great Lakes region. Individual states do not operate in a vacuum but are directly impacted by activities in the other Great Lakes states. The structure of the simultaneous equation model presented here captures these interdependencies. Such state-level results have been produced, to date, for Indiana.

The model's simulation capabilities are represented by the *mean absolute percent error* (MAPE) for each endogenous equation (i.e., the average error for the forecasts of the endogenous variables over the sample period). Most of these are less than five percent. In fact, 21 of the 44 endogenous variables of the model have MAPEs less than five percent, and another 16 are less than ten percent (see Table 1 for subset of values). This is very good to excellent performance for a regional econometric model. Analysis of the model's tracking behavior also

indicates that the model captures the turning points of the economy quite well. In most cases, the large majority of directional changes in the growth of the endogenous variables is captured by the simulation. This ability to capture economic turning points and the relatively low values for the MAPE statistics indicate that the model works well over the simulation period. However, four equations remain problematic, with MAPEs over 20 percent: state forest use, state employment in mining, state total energy consumption, and state wages in agriculture.

The next step in the research is to tune the model so that the final problem equations have acceptable MAPEs. Following this stage, we will convert the model to a two-stage least squares (TSLS) framework to eliminate simultaneous

equation bias. The implications of this bias is that the estimators are not consistent, i.e., they will not converge on their true population values regardless of the sample size. The TSLS estimators account for simultaneous equation bias and do not transmit single-equation specification errors throughout the model structure. Although slight improvements in parameter estimates are expected as a result of TSLS, these should not impact the overall performance of the general results of the model as discussed here.

Following these methodological effects, the forecasting and policy analysis elements of the second year of the project will be addressed. This stage should begin within the next few months.

Students: During the first year of the research project, funding was used to support one Ph.D. Student, 2 masters students and one undergraduate/accelerated masters student. Other student support was funded independently or on a contracted hourly basis. The funding for students was distributed as follows:

<u>Name</u>	<u>University</u>	<u>Degree</u>	<u>Contribution</u>	<u>Funds</u>
Mark D. Hilton	Indiana University	Ph.D.	50%	\$5,570
James Greco	Indiana University	MPA	50%	\$7,000
Seth Tyler	Indiana University	MPA	50%	\$7,000
Sean Gailmard	Indiana University	Accel. MPA	25%	\$2,425
Kyle Dreyfus	Indiana University	MPA	50%	Funded externally
Steve Driehaus	Indiana University	MPA	50%	Funded externally

Papers: Since the first year of the research was entirely devoted to developing the model, no papers were presented or published. However, two students working independent from the project have written a report for the State of Indiana with respect to initial state-level results produced by the model. This report highlights the potential impacts of climate change on the Indiana economy. The investigators are currently arranging to present the current findings at an appropriate conference. One or two journal papers are expected in the second year of this project.

Variable	Great Lakes Mean Absolute % Error
<i>Employment</i>	
Construction	4.29
Farming	2.76
Finance, Ins. and Real Estate	6.59
Manufacturing	6.31
Services	10.86
State and Local Government	9.55
Transportation and Utilities	4.64
Retail Trade	2.95
Wholesale Trade	5.02
Agriculture, Forestry, Fisheries	8.56
Total Employment	1.95
Unemployment Rate	8.20
<i>Wages</i>	
Construction	5.40
Farming	33.00
Finance, Insurance and Real Estate	3.44
Manufacturing	1.98
Services	1.28
State and Local Government	1.16
Transportation and Utilities	2.87
Retail Trade	.67
Wholesale Trade	1.46
Agriculture, Forestry, Fisheries	6.37
Total Annual Wage Rate	3.13
<i>Other Variables</i>	
Total Population	0.93
Net Migration	12.48
Per Capita Income	3.21
Total Personal Income	3.34
Per Capita Gross State Product	4.97
Gross State Product	5.12
Earnings by Place of Work	4.13
Dividends and Interest Income	10.21
Net Energy Consumption	20.11

Table 1. MAPES values for selected variables.

Aboveground and Belowground Ecosystem Responses to Elevated Atmospheric CO₂

James Teeri, University of Michigan

Peter Curtis, Ohio State University

John Lussenhop, University of Illinois, Chicago

Kurt Pregitzer, Michigan Technological University

Donald Zak, University of Michigan

Objectives: Our research is focused on understanding the extent to which forest ecosystems will store more or less C as atmospheric CO₂ increases over the next several decades. We are testing whether soil N availability is the primary factor regulating changes in net primary productivity in response to increased atmospheric CO₂. We hypothesize that greater plant litter production under elevated CO₂ will eventually lead to increased microbial activity and net N mineralization.

Products: Improve the understanding of the interactions between CO₂ assimilation at elevated atmospheric CO₂, whole plant growth, soil microbial and invertebrate populations, and soil N availability.

Approach: In May 1994, we established an array of 20 large open-top chambers (2.4 m tall and 3 m in diameter) at the University of Michigan Biological Station to investigate the interactive effects of atmospheric CO₂ and soil N availability on the cycling of C and N between plants and soil microorganisms. Our experiment consists of factorial treatments of atmospheric CO₂ (ambient and twice-ambient) and soil N availability (low and high) arranged in a randomized complete block design; each treatment combination is replicated five times. We constructed large-open bottom root boxes, 20 cm in depth and 3.5 m on each side, to manipulate soil N availability and to contain the root systems of *Populus tremuloides*. Two contrasting soil fertility treatments were established by filling the boxes with either 100% locally excavated Kalkaska series topsoil (Typic Haplorthod, high N treatment) or a homogenized mixture of 20% topsoil, and 80% native Rubicon sand (Entic Haplorthod, low N treatment). Net N mineralization in the two treatments, assayed by a 9-week laboratory incubation, was 348 ug N g⁻¹ d⁻¹ in the high N treatment and 45 ug N g⁻¹ d⁻¹ in the low N treatment. These rates bracket those occurring across a range of forest ecosystems in northern Lower Michigan. Each

root box contains eight minirhizotron tubes to capture images of developing *Populus* roots, and an open-top chamber rest on the soil surface of each root box.

Each open-top chamber/root box contains twelve saplings propagated from root cuttings of six local *P. tremuloides* genotypes (2 individuals of each genotype). In three of the genotypes, leaf senescence occurs in early fall, approximately 2-3 weeks earlier than leaf senescence in the other three genotypes. Dr. Burton Barnes (Univ. of Michigan) has studied the phenology of these genotypes over the past 30 years, and the differences in senescence among them are highly robust. Root segments from each clone were collected in October 1993, and plant material was propagated from these cuttings. The plants are now well established and are in their second growing season in the respective CO₂ treatments. The saplings received supplemental water to aid in their establishment (1994), but now only receive water from precipitation.

Leaf area and stem volume of each tree was determined in 1995 by measuring length and diameter of the 1994 growth, length and proximal diameter of each branch and the main stem, and the length and width of an average leaf on each branch. A subsample of leaves was collected in early June for construction of clone-specific allometric equations relating leaf dimensions and branch length and diameter to total leaf area. The first set of leaf area determinations occurred during the week of June 19, 1995 and will be repeated in early August and mid-September.

Leaf gas exchange was evaluated mid-season in 1994 using an ADC LCA3 portable photosynthesis system. Photosynthetic rate and stomatal conductance was measured at growth CO₂ concentration and at two fixed leaf internal CO₂ levels, 270 and 560 ul l⁻¹ CO₂, in all treatments. This allows us to evaluate photosynthetic acclimation to elevated CO₂. For

the 1995 growing season, two new photosynthesis systems (LI-6400) were purchased with outside funds. These state-of-the-art systems will allow much better temperature and CO₂ control as well as enable us to increase our sample size. We have recently completed our first gas exchange survey (late June, 120 plants) and plan two more surveys (early August and early October). We will also conduct extensive evaluations of photosynthetic light, temperature, and CO₂ response relationships in mid-season 1995.

Leaf tissue secondary chemistry (condensed tannin content) was evaluated mid-season in 1994 from high fertility plants only and will be measured three times in 1995 from all treatments. Whole leaves are excised from plants, flash frozen in liquid N₂, lyophilized, and tannins extracted from pulverized, dried tissue. In 1994, tannin content was quantified spectrophotometrically and evaluated against a quebracho tannin standard. In 1995, tannins will be assayed using the radial diffusion technique using a *P. tremuloides* standard.

Root growth and demography is monitored with minirhizotrons and video imaging equipment. In 1994, root images were collected for three sampling periods spaced at three or four week intervals beginning in mid-July. Root imaging is continuing in 1995 with the first image taken the week of June 11 and subsequent sets to follow every three weeks until leaf senescence.

Soil and root respiration will be determined several times during 1995. Soil respiration measurements consist of a 12L HDPE cuvette set into a permanent aluminum frame in the center of the chamber. A gas sample is extracted with a syringe every 15 min. for 45 min. and analyzed for CO₂ concentration with a gas chromatograph. The first measurements occurred on June 26 and subsequent measurements will be made every three weeks. Root respiration will be determined with a Hansatech O₂ electrode on fine (<2mm dia.) roots taken from a 20 cm soil core from each chamber. The first measurements occurred on June 30, 1995 and will be repeated every 3 weeks.

Zero tension lysimeters were installed in late June, 1995. They consist of PVC pipe cut length-wise and set at 20 cm. The end of the pipe protrudes from the side of the chamber platform and drains into a 100 ml HDPE nalgene

bottle. Soil solution samples will be collected after each rain (or every two weeks in the event of frequent rain) for determination of DOC.

Rates of microbial respiration and labile organic C pools will be assayed from soil cores using a modified microlysimeter technique. We will also use this technique to determine rates of net N mineralization and labile organic N pools. ¹⁵N will be used to determine if elevated CO₂ has influenced soil N dynamics at both levels of initial N availability. A short-term isotope dilution experiment will be used to quantify gross rates of N mineralization, microbial immobilization, and nitrification.

Responses of soil biota to treatments will be assessed with soil samples and with weekly minirhizotron video images. Variables to be measured are: length of mycorrhizal roots and the volume of fungal tissue in the roots, the concentration of phosphorus in individual vesicles of mycorrhizae as well as the length of mycorrhizal hyphae in the soil. In order to assess the response of decomposer populations the following are being measured: decomposition rate using standard cotton cloth, earthworm number and activity using mass and C/N ratio of earthworm casts, and density of earthworms and other soil invertebrates using video images from minirhizotrons.

During FY94 we were also involved in the analysis of samples taken in previous years. We used a molecular technique, phospholipid fatty acid analysis (PLFA), to gain insight into the composition of soil microbial communities beneath *Populus grandidentata* grown in 1991 under ambient and twice ambient CO₂. PLFAs extracted from rhizosphere and non-rhizosphere soil were derivitized and identified using gas chromatography and mass spectrometry. We also tested the hypothesis that leaf litter produced at elevated CO₂ in N-deficient soil would slow C and N transformations in soil. Soils were amended with *Populus euramericana* leaf litter produced in 1993 under ambient and twice ambient CO₂ and low and high soil N availability. Kinetic parameters for microbial respiration and net N mineralization were determined on litter-amended soil during a 32-week laboratory incubation.

Results to Date: FY94 was largely devoted to the establishment of the large chamber array and the planting and successful establishment of 240

Populus tremuloides seedlings. We were also very active in bringing our previous NIGEC supported research into peer-reviewed publications (see Publications List). However, we have several lines of preliminary data from the experiment with *P. tremuloides* as well as results from previous NIGEC supported studies that were analyzed in FY94.

The bulk of our preliminary data are from gas exchange and leaf chemistry studies. The aspen seedlings showed a significant stimulation of photosynthetic rate (i.e., assimilation rate at growth internal CO₂ concentration) at both fertility treatments, but the magnitude of this stimulation was less at low than at high fertility soil. When assimilation in elevated and ambient plants were compared at similar C_i, there was no difference at high fertility but a significant reduction in elevated vs ambient CO₂ at low fertility. This suggests CO₂ induced downregulation of photosynthetic capacity in low but not in high fertility soil. Similar results appear to be emerging from more extensive measurements made in early 1995.

Analysis of leaf condensed tannin content indicated significant differences among aspen clones in tannin production and in their response to growth at elevated CO₂. Among clones we found a more than two fold difference in levels of condensed tannin present in leaf tissue from plants in high fertility soil (we did not analyze plants from low fertility soil). There was no CO₂ effect on tannin content across clones: ambient grown plants had similar contents as did elevated grown plants. However, not all clones responded in the same fashion. One clone, number 51E, had significantly lower tannin content at elevated than ambient CO₂, suggesting a genotype by CO₂ environment interaction for this trait.

Results of our soil PLFA analysis from the *P. grandidentata* study showed that after one growing season, the proportions of bacterial, actinomycetal, and fungal PLFA were not significantly influenced by CO₂ environment in either rhizosphere or non-rhizosphere soil. However, clear differences were present between microbial communities in rhizosphere or non-rhizosphere soil. Although enhanced belowground plant litter production under elevated CO₂ increased the biomass of soil microorganisms, we have no evidence that such an increase occurred through a shift in community composition, at least in the short

term.

In our study of soil N dynamics and microbial respiration in soil amended with leaf litter from our *P. euramericana* study, we found that N mineralization was a linear function of time and was not significantly different for soils amended with leaves grown at elevated or ambient CO₂. While CO₂ treatments affected the soluble sugar concentration of leaf litter, it did not affect starch concentration or C:N. Microbial respiration, microbial biomass, and foliar C:N were affected by soil N availability but not by CO₂ treatment. Consequently, we found no evidence for the hypothesis that leaf litter produced at elevated CO₂ will dampen rates of C and N cycling in soil.

Manuscripts in preparation and submitted:

Zak, D.R., D.B. Ringelberg, K.S. Pregitzer, D.L. Randlett, D.C. White, and P.S. Curtis. 1995. Soil microbial communities beneath *Populus grandidentata* Michx. grown under elevated atmospheric CO₂. *Ecological Applications* (in press).

Pregitzer, K.S., D.R. Zak, P.S. Curtis, M.E. Kubiske, J.A. Teeri, and C.S. Vogel. 1995. Atmospheric CO₂, soil nitrogen and turnover of fine roots. *The New Phytologist* 129: 579-585.

Curtis, P.S., C.S. Vogel, K.S. Pregitzer, D.R. Zak, and J.A. Teeri. 1995. Interacting effects of soil fertility and atmospheric CO₂ on leaf area growth and carbon gain physiology in *Populus x euramericana*. *The New Phytologist* 129: 253-263.

Curtis, P.S., E.G. O'Neill, J.A. Teeri, D.R. Zak, and K.S. Pregitzer. 1994. Belowground responses to rising atmospheric CO₂: implications for plants, soil biota and ecosystem processes. *Plant and Soil* 165: 1-6.

Curtis, P.S., D.R. Zak, K.S. Pregitzer, and J.A. Teeri. 1994. Above- and belowground response of *Populus grandidentata* to elevated atmospheric CO₂ and soil N availability. *Plant and Soil* 165: 45-51

Curtis, P.S., D.R. Zak, K.S. Pregitzer, J. Lussenhop, and J.A. Teeri. 1995. Linking above- and belowground responses to rising CO₂ in northern deciduous forest species. In: G.W. Koch and H.A. Mooney (eds.), *Terrestrial Ecosystem Response to Elevated CO₂*.

Academic Press, NY.

Randlett, D.L., Zak, D.R., Pregitzer, K.S., and P.S. Curtis. Elevated atmospheric CO₂ and leaf litter chemistry: influences on microbial respiration and net N mineralization. (submitted, Soil Sci. Soc. Amer. J.).

Presentations:

Curtis, P.S. 1994. Leaf level gas exchange and carbohydrate metabolism at elevated CO₂: is a consensus emerging? Ecological Society of America annual meeting: symposium 'Trees and forests in a CO₂-enriched atmosphere.

Teeri, J.A. 1995. Potential ecological consequences of elevated atmospheric CO₂.

Executive board of the Society of Environmental Journalists. Ann Arbor, MI

Lussenhop, J. 1995. Response of the soil biota to elevated CO₂. Soil Ecology Society International Conference, Fort Collins, CO.

Kubiske, M.E., C.J. Mikan, J.B. Courteau, D.R. Zak, K.S. Pregitzer, and J.A. Teeri. 1995. Late-season carbon assimilation of four *Populus* clones in relation to CO₂ and soil fertility. Ecological Society of America, Snowbird, UT.

Student participation: Carl Mikan 50%, Kennetha Mays 50%, Jennifer Wasowski 25%, Xianzhong Wang 50%, Jacqueline Courteau 25%, Amy Treonis 50%.

The Effect of Variability in Microclimate and Regional Climate on the Productivity of Neotropical Migrant Landbirds in Midwestern Forests: Application to Climate-Change Scenarios

Donald R. Whitehead, C. Susan B. Grimmond, and Scott M. Robeson
Indiana University

Objectives: The impacts of climatic change and variability on four abundant Neotropical migrant birds (NTMB) are being investigated in a variety of forest contexts in south-central Indiana. Our focus is on two understory species (Acadian Flycatcher, Wood Thrush) and two ground nesting species (Worm-eating Warbler, Ovenbird). Understanding climatic impacts on NTMB is critical since a variety of factors – such as landscape fragmentation, loss of wintering habitat – may lead to fluctuations in NTMB populations. Quantifying the role of climatic variability in Midwestern forests will provide important information for a variety of scientific and policy questions.

Products: A variety of unique datasets are being developed, including extensive data on NTMB productivity. Information on brood size, number of Cowbird eggs, date of hatching, number of nestlings, the occurrence of predation or date of fledgling have been recorded. NTMB data from south-central Indiana now are available from 1991-1995. Climatic data include

measurements of air temperature, humidity, solar radiation, net all-wave radiation, wind speed, soil heat flux, soil temperature, and soil moisture at a variety of sites in Hoosier National Forest during 1994 and 1995. Other key products from this research are the models that relate climatic variability to insect abundance and NTMB productivity.

Approach: Intensive nest monitoring has been used to estimate a variety of productivity measures. Comprehensive micrometeorological data also are being collected at a number of forest sites. The impacts of climatic variability on NTMB may be both direct (e.g., thermal and moisture stresses) and indirect (e.g., insect abundance, loss of habitat); therefore, our data collection and modeling strategies consider both types of impacts. Together with variables derived from landscape pattern, climatic variability on a variety of spatial scales are being used to develop models that explain observed variability in NTMB productivity.

Results to Date: Regional climatic data from National Weather Service stations and field data from within-forest sites are being used in conjunction with data from intensive nest monitoring to assess the role of climatic variability. To assess the role of regional climatic variability, transfer functions that relate regional climatic data to within-forest variability are being developed. Preliminary analysis of climatic data suggests that moisture availability during late spring may be a key variable in NTMB productivity. Data from 1991-1994 indicate that lower overall reproduction rates are associated with dry conditions.

The four-year data set for the interior sites shows appreciable variation in reproductive success for the Acadian Flycatcher. A higher proportion of nests fledged in 1992 and 1993 (50.0% and 57.6% respectively) as compared to 1991 and 1994 (in which fledging rates were 32.7% and 36.4% respectively). The overall survival rate for Acadian Flycatchers averaged across all nest stages was correspondingly higher in 1992 and 1993 (0.447 and 0.506 respectively) than 1991 (0.286) or 1994 (0.359). Consequently the average number of young produced per pair was higher in 1992 and 1993 (1.89 for both years) than in 1991 and 1994 (0.96 and 1.50 young per pair respectively). Although there is higher productivity in 1992 and 1993, none of the between-year differences are statistically significant.

A preliminary analysis of historical climate data for the region (1951-1990) indicates some patterns that may relate to the observed variation in nest success. For example, the June monthly maximum temperatures were higher than mean by about 5°C in 1991 and 1994; May was also warmer in 1991. In addition, June daily average precipitation was higher than average in 1993 by about 6mm/day, while July daily average precipitation in 1992 was higher by 5mm/day. This suggests that cooler, moister conditions in late spring and early summer may favor higher productivity.

One explanation that is being explored is the relationship between climatic conditions and insect abundance. Insect samples taken using Malaise traps during 1993 and 1994 show that the pattern of insect abundance differed between and within years. In 1993, there was no significant difference between months (May-July)

in overall insect abundance. However, when the insects were subdivided by body length, the quantity in the class 7.5-10 mm was significantly lower in July than in June ($p=0.012$; ANOVA, pairwise comparison of means). The pattern was quite different in 1994. The count of insects from all traps dropped significantly from 13,389 in May to 8,103 in June ($p=0.016$). There was also a further significant drop between June and July ($p<0.01$), although this was not evident in the largest size category (body length >10.5 mm).

Acadian Flycatcher nests were observed throughout the summers of 1993 and 1994 in order to assess the type and quantity of food items brought to the nestlings. The nestlings were fed exclusively on arthropods in both years. The nestling provisioning rate was significantly lower in 1994 than in 1993 (4.31 and 7.94 arthropods/nestling/hour, respectively; $p<0.01$, T-test). Further nest observations are being conducted in 1995.

Within-forest climatic variability also has been observed, with ridgetop sites being warmer and drier than ravine sites. The differences in air temperature and water vapor pressure between ridgetop and ravine locations exhibit strong diurnal patterns. These climatic differences help to explain a variety of key variables, such as patterns of nesting locations and insect abundance.

Publications and Presentations: None as yet.

Student Participation: A large number of graduate and undergraduate students from the Departments of Biology and Geography at Indiana University have participated in field work and data analysis. The project has provided a great deal of valuable data, but has also acted as a unique vehicle for instructing students in experimental design, sampling methods, the use of instrumentation, etc. Listed below are the participating students and the degree they are seeking.

Lisa Angelos (M.S.), Linda Evers (M.S.), John Gano (M.S.), Elizabeth Geils (Ph.D.), Mark Hubble (Ph.D.), Michael Janis (Ph.D.), Donnelle Keech (M.S.), Thomas King (Ph.D.), Mark McKee (B.A.), Neal Schroeder (B.A.), Karen Seeh (B.A.), Karsten Shein (M.A.), Bernadette Slusher (M.S.), Jane Southworth (M.A.), Andrew Struck (M.S.), Kevin Willsey (B.A.), Amanda Zidek (B.A.).

Maximum and Minimum Temperature Variations in a Perturbed Climate and Implications for Specialized Agriculture in the Great Lakes Region

Julie A. Winkler and Jeffrey A. Andresen
Michigan State University

Objectives: Impact studies primarily have dealt with projected changes in mean climatic states, which may poorly reflect the possible influence of a perturbed climate on natural ecosystems and human activities. Instead, an indication of the expected changes in the frequency of extremes, such as the occurrence of specified conditions and thresholds, is necessary. Thus, the challenge facing modelers and impact researchers is how to develop realistic climate scenarios at the requisite time and space scales.

Specialized agriculture (i.e., fruit and vegetable production) provides a particularly challenging system in which to evaluate the possible impact of climate change, as it is sensitive to temperature extremes. For example, deciduous fruit trees are vulnerable to cold damage during autumn before the tree is adequately hardened, during the dormant period when severe cold events may freeze flower buds and wood tissue, and during spring bloom when temperatures slightly below freezing may kill flower buds following the loss of cold hardiness. An adequate evaluation of the potential impact of a perturbed climate on fruit production requires, at a minimum, time series of daily maximum and minimum temperature.

The objectives of this study are to 1) evaluate the adequacy of daily simulations of screen temperature from a particular GCM, the Canadian Climate Center (CCC) model, for application in agricultural impact analyses at fine time and space scales, 2) develop statistically-derived transfer functions for "downscaling" temperature simulations from the CCC GCM to a local, daily scale for six locations in the fruit-growing areas of the Great Lakes region, and 3) analyze the transfer-function series for a perturbed climate in terms of thermal parameters relevant to specialized agriculture.

Products: 1) A detailed evaluation for the Great Lakes region of CCC model control ($1\times\text{CO}_2$) simulations of daily maximum and minimum temperature, sea-level pressure, and 500 mb geopotential height. 2) Evaluation and comparison of several regression-based transfer-

function methodologies. 3) Transfer function-generated daily series of maximum and minimum temperature for control and perturbed ($2\times\text{CO}_2$) climates for six lake-influenced locations. 4) An assessment of the changes in the frequency or timing of critical temperature thresholds under a perturbed climate scenario. 5) Estimation of the possible changes in growing season heat accumulation for a perturbed climate.

Approach: Our first task was to evaluate whether CCC GCM daily temperature simulations can be directly utilized in impact studies. Simulations for nearby gridpoints were interpolated to a site with a high-quality observational record (Eau Claire, Michigan). The observed and simulated series were then compared using frequency distributions, daily and monthly descriptive statistics, and extreme value analysis.

The second task was to develop and evaluate transfer function methodologies. The methodologies utilized here are based on the National Weather Service's Perfect Prog (PP) and Model Output Systems (MOS), originally developed for short-range forecasting. Both the PP and MOS systems use regression techniques to formulate specification equations for individual locations which relate predictor variables, primarily free atmosphere variables, to predictands, typically surface-based variables. These techniques are based on the assumptions that free-atmosphere variables are forecasted more accurately than surface parameters and that regression equations implicitly incorporate local, site factors.

Applying the PP and MOS methodologies to GCM simulations first required that 1) the accuracy of the GCM simulations of the predictor variables be assessed, and 2) the impact on the transfer function-generated series of several user decisions such as function form and seasonal definition be evaluated. To accomplish the latter task, several variants on the regression-based methodology were explored. All transfer functions were calibrated using observations for the 1975-84 period and validated on the 1965-74

period before being applied to the CCC GCM simulations. The candidate predictor variables were limited to parameters derived from 500 mb geopotential height (Z500) and sea-level pressure (SLP).

The simplest of the transfer function methods we explored, which we have grouped under the heading "perfect prog", relates the predictor variables to the predictand (daily maximum or minimum temperature) via stepwise regression either for the entire year (PN), traditional or "fixed" seasons (PS), or for "floating seasons" (PD). The advantage of using floating seasons is that the beginning and ending dates of the periods are allowed to shift for a perturbed climate, when traditional seasonal definitions may be inappropriate. In order to account in part for any error in the GCM-simulated SLP and Z500 fields, transfer functions also were developed using standardized predictor variables (types ZN, ZS, and ZD). A third set of transfer functions were developed using the natural log of the predictand (LN, LS, and LD). Although the relationship between the predictors and predictand is highly linear for the 1975-84 calibration period, a comparison of the linear regressions against a more conservative logarithmic relationship allows us to partly assess the possible consequences of assuming a linear relationship outside the period for which the equations were developed (i.e., for a perturbed climate). Finally, transfer functions were developed using standardized predictor variables and the natural log of the predictand (XN, XS, and XD). The transfer function types were evaluated by comparing 1) daily and monthly statistics of the observed 1965-74 series and the transfer function-generated series for the validation period, 2) monthly statistics for the transfer function-generated $1\times\text{CO}_2$ series to observed values for 30 overlapping decades, and 3) daily mean and extreme temperatures for the $1\times\text{CO}_2$ period to 1950-1979 observed values.

Results to Date

GCM $1\times\text{CO}_2$ Comparisons. The comparison of the maximum and minimum temperature series for the original CCC control simulation (GCM $1\times\text{CO}_2$) with observed series for Eau Claire indicated that the GCM $1\times\text{CO}_2$ series are not a satisfactory representation of present-day conditions. Although modeled mean annual maximum and minimum temperature are within 1.5°C of the observed values, several monthly

means, particularly during spring, substantially differ from observed values. At the daily scale, the GCM $1\times\text{CO}_2$ daily means for both maximum and minimum correspond well with observed values from the end of July into December. During the remainder of the year, daily means for the two series deviate substantially, particularly for minimum temperature with the GCM-simulated daily mean persistently below the observed value in late winter and early spring and above the observed in summer and early fall. A striking characteristic of the GCM $1\times\text{CO}_2$ simulation is the unrealistic 'thresholds' during spring and autumn when both maximum and minimum temperature hover near freezing for extended periods and daily temperature range is extremely small. These "thresholds" also are evident in the CCC GCM $2\times\text{CO}_2$ series, although their timing and extent differs from the control period. As a result, GCM daily and monthly statistics, and also GCM seasonal and annual statistics, are questionable for locations where freezing temperatures are frequent. In particular, perturbed minus control comparisons for either point locations or latitudinal bands are potentially invalid. A comparison of daily means of CCC GCM control simulations of SLP and 500 mb height to observed values indicates that these variables are much more accurately simulated than screen temperature. Average daily SLP for the GCM $1\times\text{CO}_2$ series is smaller than observed from July through September, but otherwise the daily averages agree well. The daily means of Z500 for the GCM $1\times\text{CO}_2$ series and observed series agree well from September through March. During the remainder of the year, the GCM-simulated Z500 values are slightly too low.

Transfer function validation. Evaluation of the statistics for the validation period (1965-74) indicates that all the transfer function types adequately simulate the observed climate. Root mean square errors range from 2.9 to 3.7°C , comparable to error terms for short-range MOS and PP forecast systems which use a larger set of predictor variables (Andresen, unpublished data). In general, minimum temperature is better simulated by the transfer functions than maximum temperature. The error terms are smaller for those transfer function types with either fixed or floating seasons than those without seasons, particularly during March-May.

A comparison of monthly mean temperatures for the GCM $1\times\text{CO}_2$ series and the transfer function-generated series for the control climate to

observed values for 30 overlapping decades (1946-84) reveals that the transfer functions much better represent the present climate than the GCM series, particularly during spring where the GCM average monthly temperatures are as much as 8°C colder than observed values. The largest errors for all transfer function types occur in spring, particularly for the methods that do not employ seasons. Also, the types with standardized predictor variables perform best. The methods with log transformed predictands perform similarly to the comparable linear versions.

Perturbed Scenarios. In general, perturbed scenarios of maximum temperature generated using the transfer functions are warmer than the GCM2xCO₂ series, particularly from November-May. On the other hand, the transfer function minimum temperature scenarios are colder than the GCM perturbed series. The greatest differences are found in January-February and June-September. An important finding of our analysis is that the perturbed series for the different transfer function types vary markedly, and impact researchers must carefully consider the type of transfer function when interpreting scenarios developed using statistical downscaling methods. Of the different transfer function methodologies, the PN, PS, LN, and LS perturbed scenarios are the most conservative, whereas the forecasted temperatures are warmest, particularly from March-May for the ZN, XN, ZN, and ZD scenarios. Only slight differences exist between the linear and logarithmic functions.

There is considerable agreement among the different transfer function types on the occurrence of first and last frost in a perturbed climate. The scenarios suggest the median first day of frost at Eau Claire will be delayed from the present by 25-35 days, and the last frost will occur 17-24 days earlier than present. Thus, the transfer function scenarios suggest that the growing season length in the fruit production region along Lake Michigan will be considerably extended in a 2xCO₂ environment. The more extreme scenarios (ZD, XD, ZN, XN) suggest the number of days per growing season $\geq 35^{\circ}\text{C}$, a general temperature threshold above which plant photosynthesis and other processes begin to slow, will increase by more than 20 days, whereas the more conservative scenarios suggest an increase of fewer than 10 days $\geq 35^{\circ}\text{C}$ in a perturbed climate.

Manuscripts in Preparation:

The simulation of daily time series from GCM output. Part 1: Comparison of model data with observations. J.P. Palutikof, J.A. Winkler, C.M. Goodess, and J.A. Andresen.

The simulation of daily time series from GCM output. Part 2: Development of local scenarios for maximum and minimum temperature using statistical transfer functions. J.A. Winkler, J.P. Palutikof, J.A. Andresen, and C.M. Goodess.

Conference Preprints and Proceedings:

Local climate change scenarios of maximum and minimum temperature for Michigan. J.A. Andresen, J.A. Winkler, J.P. Palutikof, and C.M. Goodess. Proceedings, First Symposium on Michigan Weather and Forecasting, in press.

The simulation of daily time series from GCM output. Part 1: Comparison of model data with observations. J.P. Palutikof, J.A. Winkler, C.M. Goodess, and J.A. Andresen. Preprints, Sixth Symposium on Global Change Studies, January, 1995, Dallas, Texas, pp. 45-48.

The simulation of daily time series from GCM output. Part 2: Development of local scenarios for maximum and minimum temperature using statistical transfer functions. J.A. Winkler, J.P. Palutikof, J.A. Andresen, and C.M. Goodess. Preprints, Sixth Symposium on Global Change Studies, January 1995, Dallas, Texas, pp. 93-98.

Presentations:

Development of local scenarios of maximum and minimum temperature using statistical transfer functions. J.A. Andresen and J.A. Winkler, First Symposium on Michigan Weather and Forecasting, March 1995, Ann Arbor, Michigan.

Local climate change scenarios of daily temperature for Michigan: Development and Application. J.A. Winkler, J.A. Andresen, J.P. Palutikof, and C.M. Goodess. 91st Annual Meeting, Association of American Geographers, March 1995, Chicago, Illinois.

The simulation of daily time series from GCM output. Part 1: Comparison of model data with observations. J.P. Palutikof, J.A. Winkler, C.M. Goodess, and J.A. Andresen. Sixth Symposium on Global Change Studies, January, 1995,

Dallas, Texas.

The simulation of daily time series from GCM output. Part 2: Development of local scenarios for maximum and minimum temperature using statistical transfer functions. J.A. Winkler, J.P. Palutikof, J.A. Andresen, and C.M. Goodess. Sixth Symposium on Global Change Studies, January, 1995, Dallas, Texas.

The construction of regional climate change scenarios using a transfer function methodology. J.A. Winkler. Department of Geology Seminar Series, Michigan State University, November 1994.

Student Participation: Greg Bierly 50%, Chi-Pi Chou 25%, Eleanor Waller 25%.

Climate Forcing by Aerosol Particles in the Midwestern United States

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Objectives: Provide reliable measurements of aerosol mass scattering coefficient and its variability with time, wavelength of light, aerosol particle size, aerosol particle composition, direction of light scattered, and relative humidity, at an anthropogenically perturbed mid-latitude continental site. Experimental results obtained at the site are being compared to results from solubility and light scattering models. Results from this research can be used to improve the confidence in predictions provided by global climate models. Results obtained from these improved models are important because they will provide more knowledgeable predictions about global change over regional length scales and time scales of seasons to possibly years or decadal times per week by research personnel. The automated instrumentation samples aerosol and then transfers the data electronically to University of Illinois and NOAA for integration and interpretation.

Ambient aerosol is sampled at 150 lpm. A slip stream of the aerosol is sampled with a condensation nuclei counter (CNC) that is used to monitor the number concentration of particles at the inlet of the aerosol stream. The sample stream is then split into five paths to allow measurement of (1) reference dry light scattering signal (s_p), (2) s_p dependence on wavelength of light, direction of light scattered, controlled relative humidity, and aerosol composition, (3) light absorption by aerosol particles, and (4) aerosol particle mass concentration and chemistry. Aerosol chemistry is characterized

with ion chromatography that detects Na^+ , K^+ , Mg^{2+} , Ca^{2+} , NH_4^+ , SO_4^{2-} , Cl^- , Br^- , and NO_3^- . Glove boxes with clean purge air are used for the preparation and weighing of the filters and impactor films in the laboratory and at the field site to assure high quality control of the gravimetric and chemical data.

Collaboration with (1) Dr. Robert Leifer, at DoE's Environmental Measurements Laboratory, is occurring to provide controlled relative humidity measurements at DoE's Southern Great Plains Site, (2) Dr. John Ogren, of NOAA, to provide instrumentation that is operating at Bondville, (3) Drs. Covert, Anderson, and Charlson, of University of Washington, to develop instrumentation and light scattering code used at Bondville, and (4) Dr. Pilinis, at University of Miami, has allowed integration of the aerosol thermodynamic equilibrium code with the light scattering code.

Results to Date: Semi-continuous aerosol monitoring has occurred since 11 August 1994. 24-hr dry particulate mass concentration is $12.7 \pm 8.2 \mu\text{g}/\text{m}^3$. 24-hr mean ionic concentrations are 4.4 concentration and total dry s_p at 550 nm is $9 \text{ m}^2/\text{g}$ ($R^2 = 0.82$). Condensation nuclei particle concentration is $6,470 \pm 2820 \text{ particles}/\text{cm}^3$. Detection limits for the inorganic ions have been measured and reduced to about 50 ppb_m. The controlled relative humidity nephelometer has been tested and calibrated with laboratory generated aerosol particles, CO_2 , and HF_6 . s_p dependence on aerosol composition,

controlled relative humidity, and particle size distribution has been measured with ambient aerosol and laboratory generated test aerosol. These results have been compared with results from a program that integrated (1) thermodynamic equilibrium code, (2) metastable equilibrium code, (3) Mie light scattering theory, (4) and experimental data files that describe aerosol particle composition and particle size distribution. Good agreement occurs when assuming an internal mixture and the remaining 50% of the mass (not characterized by ion chromatography) is a carboxylic acid. These comparisons have indicated that accurate knowledge of the interaction between water and aerosol particles is crucial with respect to the accuracy and reliability of the modeled results. There is also a clear dependence of σ_{sp} and its dependence on controlled relative humidity, with origin of air mass.

We have also developed a database of results that allow easy comparison of aerosol filter data, aerosol light scattering data, aerosol composition, and meteorological parameters, such as air mass trajectories. This research is currently expanding the database that can then be used by large-scale climate models. Predictions from these models can then be used to establish policies pertaining to issues such as "greenhouse warming.

Publications:

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Site, 88th Annual Meeting of the Air and Waste Management Association, June, San Antonio, TX, 15 pp., 95-TA36A.04.

Hahn, K.L. (1995) Ambient Aerosol Particle Chemistry at a Mid-Latitude, Northern Hemispheric, Continental Site and its Relation to Global Climate Change, Master of Science thesis, University of Illinois at Urbana-Champaign, pp. 155.

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Koloutsou-Vakakis, S. and Rood, M.J. (1994) The $(\text{NH}_4)_2\text{SO}_4$ - Na_2SO_4 SO Ambient Aerosol Particles and Climate Change, invited lecture for Clean Air Societies of Australia and New Zealand, University of Queensland, 3 November.

Climate Change Effects on Agriculture in the Midwestern Great Lakes Region

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Objectives: To examine the effects of climate change on production levels of important crops at high spatial resolution by estimating the agricultural potential of the Midwestern Great Lakes region (Michigan, Illinois, Indiana, Ohio, and Wisconsin) and its sensitivity to climate change.

Products: A high resolution map of predicted changes in potential crop productivity which relates crop yield to environmental variables will be produced. These variables will include: elevation, monthly temperature and precipitation, growing degree days, moisture index, soil texture, and soil nutrient levels. A map depicting relative risk to agricultural systems from climate change will also be created for the region. Suggestions for possible adaptations in high risk areas that might influence future production and yield of targeted crops in the study area will be made.

Approach: The initial crops chosen for inclusion in the study are: corn and soybeans. These were chosen due to their economic significance in the region. Other crops may be chosen for detailed study at a later time, based on their relative importance to local economies in the Great Lakes region, and the percentage of national production of particular crops the region is responsible for.

Current geographic distribution of crops and spatial patterns of agricultural cropping systems in the Midwestern Great Lakes region have been examined. These data were used in conjunction with climatic and agricultural yield data for the five state region to serve two main purposes: (1) to construct statistical models of crop productivity as it relates to environmental variables, and (2) to satisfy input requirements for the agroecosystem model CENTURY 4.0.

These statistical productivity models have provided a method by which future crop yield patterns can be estimated in the absence of any significant climate change. These estimates will be compared with those from the process-based CENTURY model, thus allowing for simple model

parameterization and validation.

After validation was completed, we began GIS-based CENTURY modeling for each county in the five-state region. All input parameters to the model, including climate data and site characteristics (soil type, soil texture, field capacity, etc.) were geo-referenced using ARC/INFO. A suite of model runs was made to capture the effects of different rotation schedules and future climatic conditions on crop yield. These runs were each compared with a baseline case in which climate and management practices were similar to those found in the region currently.

To calculate relative risk factors for each county, we will make runs of the model using a wide range of parameters to address the uncertainty of several inputs to the model. This sensitivity analysis will be a useful technique in assessing the validity of our results. A map of these risk factors as they change across the region, and over different biotic and abiotic factors, will be created.

Results to Date: We have created several large digital databases for the study region: NCDC climate data for each weather station in the region, including monthly temperature and precipitation normals; USGS land use and land cover (LULC) at 1:250,000 scale; USGS elevation data (DEM) at 1:250,000 scale, USDA soil data (STATSGO), including variables such as soil texture, soil depth, ground-water table depth, and rock content; USDA-NASS crop data, including county-level crop production and yields by species for 1973-1992; state-produced agricultural statistics containing information on county-level production by crop, agricultural inputs (e.g. irrigation and fertilization) and economic aspects of these crops; and cultivar-specific data on corn and soybeans.

Statistical models which relate climate variables (such as growing degree days, moisture index, monthly temperature, and precipitation) to agricultural productivity were developed for all counties in the five state region. In some cases,

these models are in good agreement with productivity data for the counties ($r^2 > 0.7$). The more robust of these models have provided a good empirical method by which to assess the potential impacts of climatic change on crop productivity. A subset of the counties in the study region were fitted with time series models developed to include productivity data, climate data and production trends during a fifty year time period. The models were validated, then the output of these models were entered into ARC/INFO and compared to the CENTURY output. The comparison indicated highly similar results were generated by the CENTURY and time series models. Findings of this study were presented at Malama 'Aina 1995 and are being published in the proceedings of the conference.

Also, least squares linear regression was used to examine the relationships between county-scale climate variables and crop yield data. The climate variables were constructed from 20 years of daily weather data obtained from more than 450 stations throughout the region, while all crop yield data were obtained from USDA-NASS. All data were geo-referenced by county, and analyzed in a Geographic Information System (GIS). Spatial trends in the factors most correlated with crop yield were evident throughout the study region. July Climate Moisture Index (CMI), for example, was found to be increasingly correlated with corn yield moving from the northern tip of Michigan through southern Indiana. These findings were presented at the 1995 Ecological Society of America annual meeting.

Baseline and climate change CENTURY runs for the entire region have been completed. The results obtained from each of these runs have

been compared, and maps were prepared which depict the predicted yield changes for each county in the region. Spatial trends in these data suggest that counties within the current "corn belt" of the Midwest stand to benefit slightly from expected climate change conditions. Average yield of corn in the corn belt counties, for example, continued to increase along a similar trend to the one evident over previous decades. In marginally producing counties outside the corn belt, however, the effects of these changes on future crop yields are predicted to be severe. In parts of northern Michigan and Wisconsin, for example, model corn yields dropped 10 - 15% as compared to the baseline case. We are presently analyzing these spatial trends in more detail.

Students: Bill Littlefield 50%, Jerry Johnston 50%, Brian Offerle 25%

Publications and Presentations:

Johnston, Jerry, J.C. Randolph, W. Fan, B. Offerle, J.L. Ehman and B.Z. Littlefield. 1995. An analysis of climatological impacts on crop growth in the Midwestern Great Lakes region. 80th Annual Meeting of the Ecological Society of America. Snowbird, Utah.

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Contrasting Successional Rates and Carbon Cycling in Eutrophic and Oligotrophic Ecosystems of Amazonia

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Long Term Objective: Examine the processes of succession along an ecological continuum from oligotrophic to eutrophic ecosystems in the Amazon Basin and the consequences in terms of carbon release and sequestration. This particular study examines one eutrophic site near Altamira, on the Xingu River Basin of the Brazilian Amazon and compares it with two oligotrophic sites in the Zona Bragantina of the eastern Amazon.

Specific Objectives: The specific objectives of the project are to carry out a comparative analysis of primary productivity, forest succession, and carbon balance in oligotrophic and eutrophic forest ecosystems in the humid tropics; to obtain field data on vegetation biomass and productivity, carbon, soil nutrient status, and land use change; to combine Landsat TM digital satellite data with the above field data using GIS techniques in order to develop and help in the calibration of carbon cycle models; estimate the rates of carbon accumulation and release in these systems; and gain a better understanding of the significance of tropical deforestation and succession in the global carbon cycle, including the role of different types of human intervention.

Products: 1) Spectral signatures for major land cover classes in this region of the Amazon. 2) Assessment of the amount of deforestation. 3) Assessment of the amount of regrowth and the amount of carbon sequestered by secondary successional vegetation in eutrophic and oligotrophic sites. 4) Demonstrated the viability of monitoring secondary successional forests in a diverse region such as the Amazon using satellite platforms. 5) Linked detailed floristic studies with spectral information to assess the impact on diversity of deforestation.

Approach: This three year project builds on research carried out earlier at one eutrophic site and extends its approach to a broader comparison of highly variant ecosystems in the humid tropics—currently responsible for the highest rates of deforestation and carbon emissions (other than fossil fuels). This

approach is based on combining remotely sensed data with field studies to monitor rates of secondary growth. This involves detailed manipulation of spectral digital information from LandsatTM, developing preliminary classification of types of vegetation, tracking the fate of forest through time (usually a decade), assessing the accuracy of the analysis through field observation, and studying the impact of factors such as soils, land use history, size of area cleared, and other factors in the rate of regrowth—and thus the amounts of carbon sequestered in growing vegetation.

Brazilian collaborators assisted us in the collection of litter from litterfall trays and decomposition litterbags at monthly intervals and shipped them to Indiana University for chemical analysis. These analyses and data will permit modeling of litter production and decomposition as functions of time and climate variables. During summer 1995 a number of process level measurements were made in order to obtain a better understanding of the carbon fixation rates of the dominant woody species of these successional forests. Using a Li-cor 6200 portable photosynthesis analyzer, photosynthetic rates of 20 dominant successional tree species were measured under a variety of conditions. Other measurements taken included diurnal characterization of 1) total solar radiation, 2) photosynthetic photon flux density, 3) air and soil temperatures, 4) atmospheric carbon dioxide concentrations, 5) vapor pressure, 6) soil moisture, 7) and soil respiration.

Results to Date: The PIs and graduate research assistants undertook field research at the study sites in summer 1994 and 1995. At each of the two oligotrophic sites they collected, in addition to the process-level data noted above: 1) history of land use; 2) vegetation stand structure and species composition; 3) biomass sampling of each class of vegetation; 4) set up litterfall collecting trays in representative successional ages of vegetation; 5) set out litter decomposition bags to be collected each month to determine decomposition rates; 6) soil samples to one meter depth, taken every 20 cm,

including bulk density; 7) took samples from litter and plant parts to be analyzed for carbon content and characterized in terms of nutrients (N, P, K, Ca, and Mg); and 8) biomass sampling using a nested-plot design.

Biomass sampling was done in 48 plots in 12 successional forest stands representing early, intermediate and late successional ages in the Zona Bragantina during summer 1994 fieldwork. An additional 150 plots in 15 successional forest sites in the same regions were sampled during summer 1995. This large increment in the number of plots sampled was a product of the growing experience of the team after summer 1994. From these sites we have determined standing crop biomass and carbon content (and are well along in determining N, P, K, Ca and Mg content) for the major vegetation compartments, aggregated by morphology (leaves, branches, boles and roots), by size class (trees, saplings, understory), litter (fine and coarse), and by roots at three soil depths (0-20, 20-40 and 40-60 cm). Leaf biomass is the dominant above-ground compartment at younger sites, whereas bole biomass becomes the dominant above-ground compartment with increasing site age. Biomass and carbon content of understory vegetation and small trees is significant in early successional sites of 1-4 years. At five years, and all subsequent ages, the understory biomass and carbon pool become minor. From 5 to 20 years, the small tree biomass and carbon pool is dominant above ground. The biomass and carbon pool of large trees becomes significant after 20 years. Biomass and carbon pool of roots shows a gradual increasing trend through time. Biomass and carbon in standing dead and litter is remarkably consistent across successional ages. However, while the biomass of living vegetation, both above ground and roots, increases with successional age as expected, carbon content of the soil is two to four times the standing crop of carbon in the vegetation in young successional sites. With increasing site age, the proportion of carbon sequestered in trees increases, although even in relatively old sites it remains less than the carbon pool in soils.

Products: Results of this work have appeared in journal articles in *BioScience* (44: 329-338, 1994); *Geocarto International* (8: 61-71, 1993); *Human Ecology* (22: 249-278, 1994); *Research & Exploration* (10: 458-476, 1994); *Photogrammetric Engineering and Remote*

Sensing (in press); three papers in the *Anais do VII Congresso Brasileiro de Sensoriamento Remoto* (1: 16-26; 2: 38-46; and 3: 202-209, 1993); two papers in the *Proceedings of the Rio-94 Congress of the Internat. Soc. for Photogram. Engineering and Remote Sensing*. (vol. 30, part 7a: 184-191). Papers are in preparation on biomass, carbon and vegetation aspects of the current work (see below).

Information from this project can inform efforts at reforestation and restoration in degraded areas of the Amazon Basin. These results may provide vital information on how to reduce carbon dioxide accumulation and buy time to find better ways to control fossil fuel emissions, deforestation and loss of biodiversity.

Next Step: Completion of this work during the current academic year will emphasize completion of the chemical analysis of plant parts and litter; completion of the supervised classification of vegetation for the larger region; completion of the assessment of carbon released and sequestered in the process of land cover transformation from mature forest through the various stages of regrowth; and completion of manuscripts pointing out the large amounts of carbon below ground (discovery of an important carbon sink), the unexpectedly high pools of carbon above ground in early succession, and the very large differences in carbon sequestering between eutrophic and oligotrophic tropical forest ecosystems—suggesting the inappropriateness of aggregating these differences in global models, unless accounting is made of the areal extent of each.

Manuscripts in Preparation:

Effects of Age and Land Use History on Secondary Successional Areas, to be submitted to *Biotropica*.

Soil Carbon in Secondary Vegetation of Amazonia, to be submitted to *Interciencia*.

The effect of soil fertility on the rate of regrowth of Amazonian vegetation, to be submitted to *Forest Ecology and Management*.

Land Use and Carbon Cycles in Tropical Forest Regions, to be submitted to *Ambio*.

Vegetation Change in the Eastern Amazon, accepted for publication by *Ecological*

*Economics.***Presentations:**

"Biomass and carbon dynamics of secondary growth forests in the eastern amazon" at Ecological Society of America meeting, 1995.

"Ecologia Humana e Monitoreamento Ambiental na Amazonia atraves de Sensoreamento Remoto" invited lecture at National School of Public Health, Rio de Janeiro, June 2, 1995.

"Global Environmental Change: the View from Amazonia" at Kumamoto Symposium, Kumamoto, Japan, Nov. 4-5, 1995. Invited paper.

"Monitoring Secondary Growth in the Eastern Amazon" at AAAS meeting, Baltimore, Md., Feb. 11, 1996.

"Deforestation and Secondary Succession in the Brazilian Amazon", invited lecture at Michigan State Univ., April 19, 1995.

"Succession after Deforestation in the Eastern Amazon" invited lecture, Univ. of Nebraska at Lincoln, Feb 2, 1995.

"Recent Research in Amazonian Deforestation and its Relation to Global Environmental Change" invited lecture at Catholic Univ. of America in Washington DC, Sept. 28, 1995.

Student Participation: Graduate Students: Maria Clara da Silva-Forsberg - 50%; Alissa Packer - 50%; Fabio de Castro - 50%; Cindy Sorrensen - 20%; Eduardo Brondizio - 20%; Bernadette Slusher - 20%.

Undergraduate Students: Joanna Tucker - 50%; JoAnne Michael - 50%.

Northeast Regional Center

Steven C. Wofsy, Director

Overview: The Northeast Regional Center of NIGEC supports research primarily in two areas of global change.

1. studies to improve understanding of the effects of forests on global concentrations of CO₂, CH₄, O₃, and other greenhouse gases, and the effects on forest resources of anthropogenic changes in CO₂, air pollution, and climate; and
2. studies of heat and moisture transports by dynamical processes in the context of the global climate system.

The Center also provides start-up support for innovative projects on a variety of subjects.

The Northeast Center strives to coordinate the research activities in these areas, to deliver value-added to the US Global Change Program through collaboration among the component projects, and by providing leverage to accomplish major cost savings through sharing of facilities and expertise. Forest studies in particular have emphasized cross-disciplinary examination of sequestration of atmospheric carbon dioxide through long-term studies of the carbon balance in the whole ecosystem and its component parts (soils, boles, subcanopy vegetation), including long-term manipulations (e.g. soil warming and nutrient inputs in the field, enhanced CO₂ in the glasshouse) and process studies (e.g. leaf gas exchange observations coordinated with whole-ecosystem gas exchange measurements).

The focus on multi-year, continuous observations has proven particularly appropriate for studying global change phenomena. Many global-scale changes occur on relatively long time scales, and involve interactions between biological and physical components of a forest ecosystem that cannot be observed or understood in short-term experiments.

Recent results have revealed many surprising phenomena. One study has found springtime temperatures and wintertime snow cover are unexpectedly important for determining the net uptake of carbon over an entire year. Another has shown clear differential response to warming by different components of soil organic carbon.

The long-term nature of the forest studies is a unique feature of the NERC program. NERC projects have provided strong research-oriented enhancements of the monitoring program and manipulations sponsored by the Harvard Forest LTER. Direct flux measurements and studies of nutrient additions have been made for over five years, and soil warming, studies of soil organic matter, and enhanced CO₂ studies for three or more years. With the inauguration of long-term studies of CO₂ uptake in Howland, Me.,

planned for 1996, we begin to extend the spatial scales of the studies. Our long-term measurement programs employ state-of-art instrumentation, which providing excellent leverage for studies of atmospheric physics and chemistry and of ecosystem-level ecology.

We are looking forward in 1996 to continuing the program of long-term measurements in NIGEC; many NERC projects have now run for sufficient periods of time to clearly demonstrate the enormous value of such studies, and NERC projects will increase emphasis on synthesis, modeling, and publication of results.

Seminars: We host a series of seminars focussing on one or more global environmental issues. This year global ozone and climate were emphasized. The Northeast Regional Center was pleased to host the following seminars in 1994-1995:

Speaker/Institution	Seminar Title
Fred Fehsenfeld, NOAA	Transport of Ozone and Ozone-precursors from Continental Sources over the North Atlantic
Henry D. Jacoby, MIT	Linking Natural and Social Science Components of Climate Change
Uwe Mikolajewicz, Max-Planck Institut Für Meteorologie	Climate Sensitivity Experiments with an Ocean General Circulation Model Coupled to a Two-Dimensional Energy Balance Model
Alan Plumb, MIT	The Stratospheric Circulation: Dynamics and Transport of Chemical Tracers
Mark Schoeberl, NASA/GSFC	Insights into Polar Ozone Depletion from Upper Atmosphere Research Satellite Observations
Richard Stolarski, NASA/GSFC	Using Measurements to Constrain Predictions of the Effects of Supersonic Aircraft on Stratospheric Ozone

Attendance ranged from fifty to one hundred researchers from Harvard and surrounding institutions. Each lecture is followed by a dinner reception at which an after-dinner discussion takes place. Seminar invitations go out via electronic and regular mail, flyers are posted around the university, and announcements are mailed to the Harvard University Gazette, the Harvard Environmental Network Bulletin, and the Boston Area Physics Calendar. The Mikolajewicz seminar took place in conjunction with the Massachusetts Institute of Technology's Center for Global Change Studies and was held on the MIT campus.

Summer Undergraduate Research Fellowships:

The Management Committee awarded eighteen Summer Fellowships from twenty-six applications. Projects were evaluated on the basis of the merit of each undergraduate, regardless of whether they are working with researchers from the northeast region already sponsored by NIGEC. Undergraduates received \$3,400 stipends for their global change research and submitted a short report at the end of the summer. Awards were as follows:

Student	Institution	Title
Geoffrey Criqui	Harvard College	Quantifying Nitrous Oxide Sources
Katherine Dewitt	Barnard College	Integration of Tree Ring Studies with Long Term Forest Plot Records in the Investigation of Carbon Storage in the Black Rock Forest
Laura A. Geer	Hampshire College	Temperature, Moisture, and Litter Controls on Soil Respiration Rates
Alison Gillis	University of Connecticut	Spatial Extrapolation of Heat and Water Vapor Exchanges in Heterogeneous Forests
Andrew Holdsworth	Brown University	Land-Use Fire Interactions and their Implications for Carbon Emissions Land Use Effects on Methane Uptake and Carbon Dioxide Emission by Forest Soil Circa Ithaca, NY
Daniel Hudgens	Cornell University	Land Use Effects on Methane Uptake and Carbon Dioxide Emission by Forest Soil Circa Ithaca, NY
Karin Kryger	Northland College	Examining the Ability of Soils to Sequester Carbon
Angela Lynch	Barnard College	Role of Tropospheric Ozone in Future Carbon Storage by the Terrestrial Biosphere
Margaret McCauley	Harvard College	Human Health Effects of Air Pollution
Christopher Nicols	Yale University	The Effect of Plants on Silica During Weathering
Chad Nielsen	Harvard College	The Effects of Anthropogenic Ozone on the Photosynthetic Uptake of CO ₂ in a Young Temperate Forest
Jesse Reynolds	Hampshire College	Controls on Soil Carbon Storage and Soil CO ₂ Fluxes
Karyn Rogers	Harvard College	Modeling Methylmercury Evolution in the Great Whale R. Watershed, Quebec

Robert Rommel	Princeton University	A Spatial Model of Anthropogenic Fluxes to the Nitrogen Supply
Caitlin Rosser	Harvard College	Carbon Dioxide Elucidation of Water Vapor and Their Implications for Long-term Climate Modeling
Avijit Sen	Brown University	Terrestrial Plant Responses to CO ₂ : Implication for Regional Studies of Global Change
Sheetal Vasavada	College of Saint Rose	Role of Ozone and its Precursors in Global Environmental Change: A Field Study
Jeffrey Yin	Harvard College	Ozone Deposition at Harvard Forest: Rates and Effects on Carbon Storage

Director's Fund:

The following projects were approved by the management committee:

Principal Investigator(s)/ Institutions	Project	Award
Eric Davidson, Woods Hole Research Center	Generalizing the core experiment work at Harvard Forest to address global change issues through mechanistic modeling of forest metabolism	7,855
Manuel Lerdau, SUNY Stonybrook	Water Stress and Isoprene Emission	10,000
Michael B. McElroy, Harvard University	The Atmosphere, an Essential Component of the Global Life Support System	4,017
Herman Sievering, University of Colorado	Preliminary assessment of coarse particle nitrate at the Harvard Forest	18,442
Richard Wilson, Harvard University	Removing Constraints That Limit Nuclear Energy Use in China and Improving Energy Efficiency	8,036

Predicting Responses of Temperate Forest Ecosystems to Elevated Atmospheric CO₂ Concentrations and Air Temperatures

F.A. Bazzaz
Harvard University

Our research is addressing the two following questions:

- How will CO₂ increase and temperature rise predicted by global change scenarios, independently and interactively influence leaf-level rates of net carbon gain? To what extent will species from the same temperate forest ecosystem differ in their leaf-level responses to elevated CO₂ and temperature? What are the consequences of these changes in leaf-level processes to forest ecosystem carbon accumulation.
- How will elevated CO₂ and temperature influence the growth, physiology, and architecture of regenerating seedlings and saplings? What mechanisms underlie the species-specific responses to elevated CO₂ and temperature? Do differences in species responsiveness to elevated CO₂ and temperature correlate with obvious ecological and life history traits?

In order to develop a mechanistic understanding, of the role of temperate forests in the global carbon budget, we must understand how elevated CO₂ and temperature predicted by global change scenarios may influence leaf-level rates of net carbon gain and whole plant growth. Foliage varies considerably through the vertical gradient of the canopy of temperate trees (Bassow and Bazzaz, in prep.), and it is likely that the different types of foliage may respond differentially to climate change factors. During the growing seasons 1993 and 1994 we have made advances along two lines of experimentation a) scaling leaf-level gas exchange of seedlings to that of mature trees; b) the interaction of elevated CO₂ and elevated temperatures on the growth and physiology of tree seedlings. With these data we construct scaling models which allow us to make inferences of mature tree leaf-level response to climate change based on seedling responses to simulated global change scenarios. During the summer of 1994, we increased the sample size of mature trees studied, by using an aerial lift to gain access to the canopies of additional mature

trees in the stand. We have measured several leaf-level gas exchange parameters ($P_{\max}$, apparent quantum yield, and dark respiration), and are in the process of measuring leaf-level chemistry (nitrogen, chlorophyll content, and carbon isotopic composition) and structure (SLW and stomatal density), as has been done for the trees adjacent to the Canopy Access Towers. With these data we will be better able to assess how representative the trees adjacent to the towers are of the stand.

1) Scaling

Leaf-level physiological parameters have often been found to differ substantially between saplings and adult trees in forest tree species (e.g. Jurik et al. 1988, Lei and Lechowicz 1991). Such differences may in part reflect leaf-level acclimation to environmental conditions, especially light (e.g. Boardman 1981, Givnish 1988), but fixed patterns of whole-plant ontogenetic change may also be important (e.g. Bazzaz 1979). In the few studies that have explicitly addressed this issue, adult tree $P_{\max}$ values have been found to scale as a simple, linear function of sapling $P_{\max}$ (Koike 1988, Thomas and Bazzaz, in prep.), thus:

$$P_{\max}(\text{adult}) = \alpha P_{\max}(\text{sapling}).$$

Plants grown in controlled environment facilities have often been found to have reduced growth and lower photosynthetic capacity in comparison to field-grown plants (e.g. Bazzaz 1973, Hickman 1975), although these differences are generally minimized in facilities that maintain high light levels and ambient light quality (e.g. Kramer 1978, Gifford and Rawson 1992). We expect that the canopy saplings will be similar to those grown under ambient conditions in the glasshouse; however, we plan to directly test this assumption, and possibly incorporate a "glasshouse effect" coefficient analogous to the above ontogenetic scaling factor: i.e.

$$P_{\max}(\text{field sapling}) = \beta P_{\max}(\text{glasshouse sapling}).$$

In the summer of 1993, we conducted an experiment to compare leaf-level traits among

populations of seedlings and mature trees. There were two main components to this experiment: 1) comparing leaf-level physiology of mature tree foliage to seedling foliage grown at two heights, canopy-top and sub-canopy; and 2) comparing leaf-level physiology of seedlings of the same species grown in the glasshouse in two simulated canopy height conditions in ambient and in elevated CO_2 atmospheres.

For this experiment we used 4 tree species: red oak, red maple, yellow birch and white birch; and 2 different C_4 species *Zea mays* and *Amaranthus retroflexus* as bioassays of the air isotopic composition. In Harvard Forest we constructed platforms at 2 heights on both of our Canopy Access Towers, at the top of the canopy and in the sub-canopy at a height of 12 meters. We placed 5 replicate seedlings of each of the four species, potted in 8-inch standard pots with a mix of 1-1-1 peat, sand and perlite, fertilized at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, and inoculated with a slurry of known mycorrhizal roots and soil. These seedlings were maintained under mesic conditions throughout the summer.

In the glasshouse, the two canopy heights were simulated with high-intensity metal halide lamps and oscillating fans for the canopy-top conditions, and 30% shade-cloth and no supplemental fans for the sub-canopy conditions. These two light and wind treatments correspond moderately well with the mean conditions observed at the two canopy heights within the forest. Data were collected to document the comparison between the glasshouse treatments and their corresponding forest canopy environments. The canopy height treatments in the glasshouse were replicated in ambient and elevated CO_2 zones, in three blocks. Five replicate seedlings of each species were placed in the simulated canopy height treatments at both CO_2 levels in all three blocks. Glasshouse seedlings were grown in 8-inch standard pots with identical soil mix, nutrients and inoculum as the field grown seedlings.

We made the following measurements throughout the course of the season:

1) Photosynthesis. We measured seasonal patterns of $P_{\text{in situ}}$, $P_{\text{highlight}}$, P_{lowlight} , and Daytime Dark Respiration (R_{dd}) of seedlings, and mature trees in the canopy as well as in the glasshouse in growth CO_2 levels using a Licor 6200 Photosynthesis System (Licor, Lincoln, NE). The

highlight measurements were made at light levels above $1000 \mu \text{E m}^{-2}$, above the light saturation point for these species, and the lowlight measurements were made at light levels of approximately $50 \mu \text{E m}^{-2}$. $P_{\text{highlight}}$ is essentially P_{max} . We also measured photosynthetic rate at saturating light and saturating CO_2 levels as a measure of $P_{\text{max max}}$. Seedling measurements began as soon as the foliage was large enough to place in the Licor 6200 cuvette. We used the most recently fully expanded foliage, and tried to make the measurements only between 8 AM and 3 PM. We also measured photosynthetic light curves for a subset of the seedlings and mature tree foliage.

2) Leaf-level Traits. We also measured a variety of traits on leaf samples taken from the seedlings in the glasshouse and the canopy, as well as the mature trees. These measurements included: stomatal peels to quantify stomatal density, chlorophyll analysis, CHN analysis, specific leaf weight (SLW), carbon isotopic composition (as a measure of the long-term water use efficiency), and leaf-to-air temperature differentials. Leaf-samples were taken in early September, before the onset of senescence.

3) Biomass production of the seedlings. We harvested the seedlings in early September for measuring total growth and allocation of the different populations of seedlings.

4) Carbon isotopic composition. We will estimate the actual discrimination by the seedling and tree foliage by correcting the observed leaf isotopic ratios by an estimate of the average air isotopic composition. Throughout the season we grew corn (*Zea mays*) and *Amaranthus retroflexus* adjacent to all populations of seedlings to monitor the air isotopic composition, as C_4 plants have been shown to have foliar isotopic compositions which are linearly related to air isotopic composition. We are in the process of also measuring the isotopic composition of air samples to determine if this linear relationship is maintained in elevated CO_2 conditions.

Analyses and Simulation Studies

The proposed measurements will provide a data base for estimates of GPP of canopies of major forest tree species under increased CO_2 and temperature regimes. At any point in the season, our projected values of P_{max} for canopy

and sub-canopy leaves in an elevated CO_2 and temperature environment will be estimated as $P_{\max} \cdot \alpha \beta$ for a particular tree species. The projected change in GPP is then proportional to the projected changes in $P_{\max}$ values for canopy and sub-canopy leaves. The total projected change in GPP includes weighting factors for LAI of canopy and sub-canopy leaves, and for species composition in the forest. The data collected will also allow for several kinds of sensitivity analyses of these projections.

Figure 1 shows $P_{\max}$ measured in the August ($\mu\text{mol m}^{-2} \text{sec}^{-1}$) for foliage from seedlings in the glasshouse at ambient and elevated CO_2 levels and from seedlings and mature trees at the Harvard Forest site. It can be seen that in some species, such as in red maple, the seedlings in ambient CO_2 in the glasshouse have a similar photosynthetic rate as compared with both seedlings and mature trees in the forest. Elevated CO_2 enhances the $P_{\max}$ for these seedlings, particularly in the sub-canopy conditions. While for other species (red oak), the mature trees are very different from any of the seedlings, and elevated CO_2 only slightly enhances the photosynthetic rate of the seedlings in the canopy-top conditions and even declines in the sub-canopy conditions. This implies that our model of the two staged scaling

parameters may be adequate for some species, while it may prove quite difficult for other species. Additional photosynthetic data remains to be analyzed before additional conclusions can be made about estimating the effects of rising levels of CO_2 on GPP.

We have also extended the small sample size of mature trees studied, by using a cherry picker to gain access to additional mature trees of the same species. On foliage from these additional trees we measured several gas exchange parameters ($P_{\max}$, $P_{\max \max}$, P_{lowlight} , R_{dd}), and are in the process of analyzing for leaf-level chemistry (nitrogen and chlorophyll content) and carbon isotopic composition, as had been done for the trees adjacent to the Canopy Access Towers.

2) Interactive Effects of Elevated CO_2 and Temperature

Our studies investigating the interactive effects of elevated CO_2 and air temperature have begun with an intensive study using yellow birch as a model species. Seedlings have been raised for 4 months in controlled CO_2 (350 and $700 \mu\text{l l}^{-1}$) and temperature (21/26 and 26/31 $^{\circ}\text{C}$ day/night) regimes, and will continue to be observed for two years. Detailed growth analysis on sequential harvests are being coordinated with numerous physiological and biochemical measurements including measures of leaf net photosynthesis, leaf dark respiration, leaf chlorophyll fluorescence, leaf nitrogen and chlorophyll content, whole shoot respiration (using a newly

designed chamber), and whole plant transpiration and water use efficiency. Results from the first year are still being collated and analyzed. Below we present some preliminary results from the 3rd of 6 harvest in the first year taken when plants were approximately 2 months old.

Elevated CO_2 , increased temperature, and their interactions significantly influenced seedling growth (Fig. 2a). While increased CO_2 stimulated net carbon gain, higher temperatures reduced it. Furthermore, CO_2 -induced growth enhancements were contingent on temperature; proportional enhancements at low temperatures were only 38%, whereas at high temperatures they were 83%. This growth result may be partially due to whole plant water relations. High temperatures greatly increased whole plant transpiration rates, whereas elevated CO_2 decreased water loss, more so at high vs. low temperature (Fig. 2b). The overall stimulating effect of elevated CO_2 on growth may have resulted from the significant reduction it caused in whole shoot respiration, however, the effects of temperature on respiration were not significant (Fig. 2c).

In the coming year (1995-1996) we plan to continue measurements of canopy and subcanopy photosynthesis using more trees and more species. This will be accomplished through the use of a cherry picker which proved to be very flexible in researching the canopy of a large number of individual trees in the tract at Prospect Hill. In addition we will continue to measure girth

growth increments in several trees and collect leaf litter to compose with the scaled photosynthesis and transpiration measurements and with CO_2 and water flux from the EMS tower being measured with eddy covariance method by Steve Wofsy and his group. We also will complete the analysis of CO_2 and H_2O data to document the degree of agreement between the methods and to gain more information on year-to-year variation in the flux of carbon dioxide and water vapor. Our data will contribute to addressing the question of the role of Harvard Forest Ecosystem and other temperate forests to the global carbon cycle.

Modern Calibration of Deep Ocean Climate Records: Multiple-Tracer Studies of Living Benthic Foraminifera

Edward A. Boyle
Massachusetts Institute of Technology

Objectives: Prediction of future atmospheric carbon dioxide levels and climate requires that we have a firm understanding of the potential for changes in deep ocean circulation. Ocean circulation models are one of the major weak links in our ability to predict future climate. In order to improve ocean models, one crucial key is the ongoing comparison of model behavior with data outlining the response of ocean

circulation to past climate changes. Oceanographers studying deep ocean climate/circulation changes and climatological changes in carbon dioxide rely on geochemical tracers ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, ^{14}C , Cd, Ba) incorporated into benthic foraminifera. Foraminifera record these properties with sufficient accuracy to establish large-scale and large-amplitude signals, but it is still uncertain whether foraminifera are sufficiently

precise to record more subtle signals which are nonetheless important. The importance of the quest justifies a renewed effort at establishing just how good foraminifera are as environmental monitors. The principle objective of our work is to improve our understanding of the accuracy with which geochemical tracers can be employed to answer questions such as these.

Products:

- The first product of this project is to improve our analytical detection limits to make multiple-tracer work feasible.
- The second product will be to devise an automated pre-sorting device that can cut down on the human effort required to find living benthic foraminifera.
- The third product of this research will be collection of a multi-tracer dataset on $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Cd/Ca and Ba/Ca in living benthic foraminifera in comparison to the bottom water chemistry.

Approach: The ultimate test of accuracy and precision is a comparison between scarce living benthic foraminifera and modern bottom water. However, living benthics are "needles in the haystack"; in a typical ocean sediment surface sample, there might be one living benthic foraminifera hidden within a million dead forams. Work of this type is hence labor-intensive and slow. Some stable isotope work on living benthics has been done, but sample sizes obtained from these studies have been insufficient to test other geochemical tracers (^{14}C , Cd/Ca, Ba/Ca). In this research, we aim to create new methods for obtaining large numbers of living benthic foraminifera needed for the calibration of multiple geochemical tracers. The first step in this effort was to improve detection limits so that smaller samples can be used. The second step in this effort has to devise better methods for eliminating clearly non-living benthics from these samples to reduce the manual effort involved in picking out "one-in-a-million" living benthic foraminifera from the fossil specimens. This objective will be one of our most important contributions, and we expect that others will adopt our technology. The final step will be to obtain data on specimens generated by this device.

Results to Date: Last year, we reported on our improved capability at analyzing very small

samples for Cd/Ca; we can now analyze individual benthic foraminifera. That work is now published. Future developments include the forthcoming acquisition of a high sensitivity ICPMS system (>20 times our current instrument) that will allow for analysis of very small specimens for Ba/Ca.

This year's progress has been in the automated picking of living benthic foraminifera from surface sediment samples. Although we had made significant progress in our initial efforts at doing this with fluorescent dye tracers, MIT employee Mike Prichard suggested a much better approach that largely uses standardized equipment and hardware rather than the specialized equipment that we had been working on.

In the new approach, developed by the PI and undergraduates Jason Mondanaro and Aaron Freedman:

- (1) Living foraminifera are stained with the traditional Rose Bengal stain. When kept wet, protoplasm-filled specimens are obvious when observed with a binocular microscope.
- (2) Our new system uses a standard flat bed color scanner (we used a Silverscanner II, although others would no doubt work as well) attached to a Macintosh computer. The scanner has an optical resolution of 400x800 pixels per inch (pixel size about 3x6 microns). The stained foraminifera (living plus dead) are spread onto the surface of the scanner in an 8" x 8" well, with a white background (to help make white dead foraminifera blend into the background).
- (3) The color scan is imported directly into Adobe Photoshop (we have used versions 2.5 and 3.0 successfully).
- (4) Using standard Photoshop manipulation tools, the contrast of red objects relative to other objects is enhanced.
- (5) The red channel of the image is subtracted from the total RGB image, producing a gray scale image where red objects are dark and other objects are suppressed grays.
- (6) This file is then converted into a simple black and white array using a 50% cutoff criterion and saved onto disk.
- (7) This disk file is imported into a custom C

program developed in PC UNIX and then converted to the Macintosh using the Code Warrior compiler. This program identifies solid black objects and draws an outline around solid black objects. The coordinate values of the outline are then averaged to derive an estimate for the center of the object. These center coordinates are then saved as a text file.

(8) Given the coordinates of the object, these are then used by another custom program to drive an X-Y-Z stepper motor system through the Macintosh serial interface. The X-Y coordinates locate an empty Pasteur pipette over the living specimens. Then, the Z stepper drops the pipette just above the specimen which is sucked up by capillary action. The program then sends the pipette back towards a sample well, and a piston inside of the pipette forces the sample out of the pipette into the well. The system is then ready to pick another specimen.

Using this system, living specimens have been identified; the system never misses real living benthics and has a false-positive rate quite a bit lower than our original 10% goal. We are testing the system now to further improve the accuracy. Pending final completion of these tests, we will then start into production mode and begin picking samples for geochemical analysis. Our first analyses will be one sample from the Atlantic continental margin provided by Dr. Bruce Corliss. We plan to document this picking device and make it available to others.

As a final item, the benthic foraminiferal culture work of Drs. Tim Shaw and Thomas Chandler (U. of South Carolina), with whom we are collaborating on geochemical studies, is underway with good progress.

Students: Jason Mondanaro, MIT, B.S., 20% spring 1995; 100% summer 1995, \$3500 (before overhead and benefits); Aaron Freedman, MIT, B.S., 30% summer 1995, \$1000 (before overhead and benefits)

Papers

Boyle, E.A. (1995) Limits on Benthic Foraminiferal Chemical Analyses as Precise Measures of Environmental Properties, *Journal of Foraminiferal Research* 25:4-13.

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Presentations at meetings:

"Chemical hydrography of the South Atlantic during the last glacial maximum: $\delta^{13}\text{C}$ vs. Cd", Conference on South Atlantic Oceanography and Paleoceanography, Bremen, Germany Aug. 1994

"Minor element incorporation into calcite shells: applications for ice age paleoceanography" Goldschmidt Conference, Edinburgh, August 1994.

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January 1995: "The glacial ocean conveyor: has it changed from the modern conveyor", Nova Scotia Academy of Sciences

forthcoming:

November 1995: "Cadmium and carbon isotope records of the carbon cycle", NAS/NRC colloquium on Carbon Dioxide and Climate Change, Irvine

Sources of Atmospheric Methane in the Eastern United States: An Integrated Assessment

Patrick M. Crill
University of New Hampshire

Objectives: Our long-term research plan has four specific tasks:

- 1) An analytical measurement system for measuring ambient CH₄ was designed and implemented at the air chemistry tower in the Harvard Forest (HF), Petersham, MA. The UNH automated gas chromatograph provides quasi-continuous, high precision measurements of CH₄.
- 2) An emissions inventory of both natural and anthropogenic sources of CH₄ is being compiled for the New England states and New York will be completed.
- 3) Analysis of the combined ambient CH₄ concentration variations and emission maps, supported by other chemical/meteorological data from the HF air chemistry tower will be used to elucidate the detection capabilities of the tower for specific local and regional sources of CH₄.
- 4) As the U.S. climate change action plan is implemented, the data from the HF tower will be a test of the potential for using continuous CH₄ measurements in a continental industrial/urban setting to detect changes in source emissions (i.e., verify that mitigation programs have worked). The issue of being able to detect change in greenhouse gas emissions is especially important to national and international global change research and policy.

Our strategy is to establish a long-term, low-budget program which can acquire the decade, or longer, data bases required for a quantitative integrated assessment of variations in the climatology of CH₄ at the HF site. The HF air chemistry tower is ideally located to sample air with trajectories over industrial/urban environments (east to southwest) and rural landscapes (west to north).

Products:

1. Our initial manuscript is being revised and a more detailed manuscript is in preparation that

will integrate selected air chemistry data, meteorological and air trajectory analyses, and CH₄ inventory results to elucidate the origin and characteristics of CH₄ pollution episodes at HF.

2. The CH₄ measurements at the HF tower are being continued to enhance the statistical characterization of CH₄ concentrations under different meteorological conditions (e.g. wind direction and speed, stability conditions, etc.) which have been undersampled to date. The temporal record will be supplemented with an exploratory spatial CH₄ survey to confirm source distributions derived from the analyses in Task 1 above.

3. The CH₄ emission inventory maps for landfill, wastewater, animals/manure, and wetlands for all of the New England states will be completed in FY95. A manuscript describing the source inventories is in preparation.

Approach and Results: We have made strong progress during FY 94 on our CH₄ measurement and emissions inventories tasks. Semi-continuous, high quality ambient CH₄ concentration data were collected at the HF tower during FY 94. An analysis of ambient CH₄ compared to a working standard that was calibrated against NOAA- CMDL provided standards was made by an automated gas chromatographic sampling system every 11 minutes. We have been improving our data acquisition from year to year and we expect to further improve data acquisition and quality control in FY95.

The variability in ambient CH₄ concentrations is correlated wind direction. Data illustrate that the highest average CH₄ concentrations occur during the time periods when air reaching the HF tower is from the southerly and southwesterly directions. High concentrations are observed from this quadrant only under conditions of modest wind speeds (0.8-2.0 m/s). At higher wind speeds (> 2.0 m/s) the methane from the SW source is presumably better mixed into the free troposphere. The lower wind speeds (< 0.8

m/s) are insufficiently strong to advect CH₄ to the HF tower from the SW source region. Air from the northerly and northwesterly sectors exhibited the lowest average concentrations. Ambient CH₄ variations are consistent with a hypothesis that the measured variability at the tower is primarily influenced by landfill emissions within a range of 75 to 200 kilometers of the HF tower.

Enhanced CH₄ correlates relatively well with CO and NO_x/NO_y during many of the high CH₄ periods. This is probably because the major landfills, e.g. to the southwest of HF, are co-located with areas of higher industrial activity and fossil fuel combustion. A detailed analysis of lead and lag relationships between changes in wind direction and changes in CH₄, CO, NO_x and NO_y will be conducted during the period covered in this proposal. These relationships, together with emission inventory maps, will provide considerable information on the "footprint" sensed by the HF tower at various times of the year, and under various meteorological conditions.

Another important consideration for determining the sensitivity of the HF tower CH₄ measurements to the spatial distribution of sources is the interaction of the seasonality in source emission fluxes with meteorological variations which influence dispersion and turbulent mixing processes. The top 10% of all measured monthly concentrations occur in late summer, fall and early winter probably due to enhanced emissions during summer and fall, combined with more frequent and persistent boundary layer inversions during late fall and winter. The relatively low peak concentrations observed in the spring and early summer correspond with periods of minimum emissions and more vigorous atmospheric mixing. These relationships need to be understood to fully assess the potential of tower measurements for determining regional sources, or for use in verifying claims of source mitigation.

Quantitative knowledge of landfill, wastewater and natural gas system CH₄ sources are especially important because they are most likely to be reduced through the use of cost-effective management methods. We have made considerable progress on compiling a state of the art CH₄ emissions inventory for New York and the New England states. Our NIGEC CH₄ emissions inventory uses a combination of modeling (and field measurements to quantitatively define the spatial and temporal characteristics of CH₄ emissions from the major anthropogenic sources in the northeastern U.S. Our model is an integrating framework built by combining submodels of specific emission sources. Each submodel incorporates the current understanding of primary socioeconomic, engineering, biogeochemical and climatic factors that influence CH₄ production and emission from that source. Maps of combined emissions from anthropogenic and natural sources are being produced with resolution at the county scale.

The emissions inventory maps will be very useful for interpretation of the variability in CH₄ at the HF tower as discussed in the previous section of this proposal. In the longer term we also plan to use the emission inventory data as input to a transport model. The modelling research will further assist in our understanding of the HF tower data, and in our evaluation of the role tower measurements can play in greenhouse gas reduction monitoring and verification.

Manuscripts in preparation and submitted:

Variability of Ambient Methane in Central New England. Submitted to Atmospheric Environment November 1994, in revision.

A Regional Methane Emissions Inventory for New England. ms in prep.

Other Products: Maps of New England methane sources at the county level.

Student Participation: Mark Shipham 100%

Observation, Analysis, and Parameterization of Forest-Atmosphere Exchange Mechanisms

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University of New York, Albany

Objectives: Our work aims:

- a) To document and describe the turbulent mechanisms that lead to energy and mass exchange between northeastern forests and the atmosphere;
- b) To relate the long-term flux data record at Harvard Forest to radiative parameters measured *in situ* and by satellite. This objective is to develop simple relationships between the directly observed fluxes and parameters that could be determined using remote sensing techniques; and
- c) To assess the effect of the forest on regional climate. We place particular emphasis on the how the seasonal presence of leaves performs a natural sensitivity study. We have documented how large seasonal changes in leaf area index (LAI) in the northeastern deciduous forests lead to an abrupt change in energy partition from sensible to latent heat flux at canopy top and a partial decoupling of the subcanopy environment from that above. The consequences of the seasonal environmental changes can be seen on a variety of time and space scales, and this has led us to consider larger questions of the effect of phenology on regional climate. At the smaller scales, we examine the mechanisms of turbulent exchange of energy and mass between the forest and the atmosphere. This includes study of subcanopy mixing processes. To extrapolate regionally from measurements at a single tower, we seek relationships between these exchanges and potentially remotely sensed quantities. We use local radiation observations as the link for this process.

Among the specific hypotheses we seek to evaluate are:

- a) The size, spacing, and intensity of the large eddies that couple the canopy layer to the atmosphere can be understood as a manifestation of shear instability at canopy top. Better understanding of the mean properties of these eddies will lead to improved estimates of the rate of mass exchange between the forest floor and the lower atmosphere;
- b) Enhanced evapotranspiration during the growing season leads to increased numbers of boundary layer clouds. Boundary layer clouds represent a key feedback link between transpiration and carbon uptake; and
- c) One can understand the maximum impact that vegetation has on regional climate (temperature, humidity, and carbon uptake) by studying changes during the spring transition to the growing season. In addition, effects of spring leaf-out can be detected using standard climatological surface observations as well as in the detailed flux time series at Harvard Forest;

Products: The products to be obtained by this work include:

- An improved understanding of how intraseasonal and interannual climate variability in the NE U.S. is related to regional carbon and water balances;
- Identification of the remotely sensed parameters (e.g., NDVI) that most closely track the seasonal changes in CO₂ and water vapor exchange properties (e.g., r_c) in a mixed deciduous forest and specify adequate simple parameterizations for models;
- Through better understanding of the canopy-subcanopy turbulent interactions, development of independent estimates of subcanopy respiration rates and their dependence on temperature;
- Developing techniques to use synoptic weather changes to assess sensitivity of transpiration and carbon uptake to altered light and vapor pressure deficit environments;
- By studying the changes in convective cloud frequency and temperature changes in the climatological record, documentation and then modeling the feedback between vegetation-modulated surface fluxes and

regional climate in the NE U.S.

Approach

Our fundamental approach to connect seasonal changes in appearance in the canopy (albedo, surface radiation temperatures) to corresponding exchanges of heat, water vapor and carbon compounds.

Three specific efforts characterize our approach:

- a) Data acquisition, both through direct observation and from outside sources. We operate subcanopy turbulence observations at the Harvard Forest EMS site, and make backup recording of the same measurements made by the Harvard Group at canopy top. During our NIGEC participation we have continually improved methods of long-term turbulence data assimilation. We work to ensure data quality for the data set collected since mid-1991, upgrading the data acquisition system and sensor suite regularly. Components of the radiative energy budget and PAR radiation have been recorded at canopy top. We now have acquired one of the longest sequences of subcanopy turbulence and flux observations, and this is making it possible to study seasonal and interannual variation in transport properties;
- b) Data analysis involving statistical and modeling approaches. We are interested in describing the process of mass exchange between the canopy and the atmospheric boundary layer. This work is important fundamentally, but it is directed specifically at improving confidence in estimates of the ecosystem respiration rate and the understory contribution to stand evaporation. Finding the source region for measured fluxes, and assessing site representativity form part of this effort.
- c) Parameterization, wherein we report our single-point observations in the framework of canopy-atmosphere exchange models used in simulation models. This work also involves relating our direct flux observations to measurements that can be made using remote sensing techniques. In addition, we seek relationships between radiative inputs to the surface energy balance, such as between downwelling long-wave radiation

and surface layer temperature and humidity.

Results during 1994-1995: New field and data analysis efforts

In addition to the ongoing flux observations, during this period we:

- Developed and installed a new data system. The system now records the radiation signals at higher frequency for the first time. The obsolete PDP-11/73 machine used to digitize signals was replaced with a Harrison datalogger. We upgraded communications to the site using higher speed modems and SLIP connection to allow X-windows graphics to be displayed on the workstations in Albany. This has led to improved data quality and reduced the required number of site visits;
- Designed and are ready to deploy a robust p' sensor, to track pressure perturbations in the subcanopy. This sensor will aid in our ongoing study of large eddies in the roughness sublayer. We also installed additional anemometers at the EMS tower at Harvard Forest;
- Began to acquire and archive a data base using the new NWS ASOS weather stations near Harvard Forest. This is being expanded to include the entire east coast. These data include directly measured cloud base as well as standard surface meteorological observations;
- Began a research activity to identify lightning strikes observed by the National Lightning Detection Network within 50 km of EMS tower during the last 4 years, to seek possible changes in BL NO concentrations (with J. W. Munger of Harvard Univ.).

Findings:

Recent work [Moore et al., 1995; Sakai et al., 1995] from our group has found:

- Global solar albedo and PAR albedo are good indicators of spring leaf-out and autumnal defoliation of the canopy;
- There is a steady, repeatable decline in solar albedo over the growing season. This is due to decreasing near-infrared reflectance, a fact borne out through comparison with satellite observations. (Figure, upper left);
- Subcanopy evapotranspiration contributes 10-20% of the total during the growing season. Daytime CO₂ flux obtained using

the eddy correlation method in the lower canopy is comparable to nighttime estimates of the respiration rate. During 1995, for example, understory evapotranspiration has contributed to 70% of the total prior to leaf out (Days 120-146) and 21% thereafter (Days 148-192);

- Satellite estimates of the Normalized Difference Vegetation Index (NDVI) track the seasonal changes in albedo measured *in situ* at Harvard Forest (Figure, upper right);
- Linear regressions relating albedo, NDVI and other parameters to the canopy resistance for water vapor transport (r_c) are robust and repeatable year to year. These can form a basis for parameterizing transpiration in models.
- Growing season changes in r_c are related to changes in the Bowen ratio. The Bowen ratio has a parabolic form during the growing season, with a minimum in early August.
- Measurements of the time series of Leaf Area Index (LAI) during two years indicate that there is a significant, repeatable relationship with r_c . That this relationship appears to be the same from leaf emergence to senescence indicates that this forest transpires as its current LAI allows. (Figure, center left).

Preliminary findings from ongoing work include:

- We have found during 1991-1994, but not for 1995, enhanced values of σ_{Kdn} , standard deviation of global solar radiation, just after the time of leaf emergence (Figure, bottom panels). Preliminary studies using the cloud base record at the Orange MA ASOS station indicates that σ_{Kdn} can be related to the fraction of small cumulus clouds forced by surface heat and water vapor fluxes. We are preparing a climatology of convective cloud presence using these data;
- The large changes in Bowen ratio at leaf out are reflected in a change in the daily rate of change of maximum temperature at climate stations in central Massachusetts (Figure, center right);
- We have continued work on boundary layer warming and moistening following cold fronts, investigating what kinds of feedbacks occur between the presence of clouds and surface heat and water vapor fluxes. This work involves study of the "recovery" process after cold frontal passage for periods of several days. We have used

simple model studies to find that entrainment flux of drier air into the upper boundary layer affects surface vapor pressure deficits (VPD) only in the initial days of recover and that, viewed in a multi-day sequence, there is little sensitivity of VPD to the entrainment parameter linking surface and mixed layer top heat fluxes;

- We are currently looking at the effects of fluctuating light, such as that caused by shallow cloudiness, on productivity. Though there is considerable literature on the role of light flecks in understory growth, the existence of large "mega-flecks" produced for cumulus fields may also be important to C uptake in the forest as a whole.

Results published, manuscripts submitted and in preparation:

Physical Mechanisms of heat and mass exchange between forests and the atmosphere", D. R. Fitzjarrald and K. E. Moore, 1995, Chap. 3 in *Forest Canopies*, ed. M. D. Lowman and N. M. Nadkarni, Academic Press, 624pp.

Seasonal variation in radiative and turbulent exchange at a deciduous forest in central Massachusetts, K. E. Moore, D. R. Fitzjarrald, R. K. Sakai, M. L. Goulden, J. W. Munger, and S. C. Wofsy, 1995, *J. Appl. Met.*, in final review.

Seasonal changes in exchange properties in a deciduous forest, R. K. Sakai, D. R. Fitzjarrald, and K. E. Moore, 1995, submitted to *Ag. & Forest Met.*

Forest-atmosphere exchange processes: Relationships between leaf state and radiative properties with regional climate 1991-1995, D. R. Fitzjarrald, K. E. Moore, R. K. Sakai, and J. M. Freedman, 6th Harvard Forest Ecology Symposium, Petersham MA, 10 April 1995.

Student participation: Ricardo K. Sakai completed his M.S. thesis "Leaf area influence on turbulent exchange in a deciduous forest", with 50% support from NIGEC. Data used in this thesis were obtained at Harvard Forest as part of NIGEC-sponsored activities. Mr. Sakai is now enrolled in the Ph.D. program. A second Ph.D. student, Mr. Jeffrey M. Freedman, has joined our group with 50% support from NIGEC. He is working on the cloud-surface flux climate feedback problem.

Figure

[Upper left] Mean daily midday global solar albedo, July 1991-December 1993. Also shown is the ratio of PAR received above the canopy to that received at 11 m (PR). (Bottom) PAR albedo for the same period (from Moore et al., 1995).

[Upper right] Time series of NDVI for the pixel that includes Harvard Forest, PAR-albedo, canopy resistance (r_c), and LAI at Harvard Forest during 1992. Vertical dashed lines indicate the period when the leaves are present (from Sakai et al., 1995).

[Center left] Linear regressions of LAI vs r_c for the leaf out period during 1992 (squares, solid line regression) and 1992 (circles, dashed line regression). The "X" corresponds to the average value of r_c from day 216 to day 275 (from Sakai et al., 1995).

[Center right] Average daily maximum temperatures (1950-1992) at Birch Dam, MA. Vertical line at day 120 approximately corresponds to leaf out

[Bottom panels] Daily averaged global solar radiation at the Harvard Forest EMS site (light lines) and σ_{Kdn} over 20 minute averaging periods (dots).

The Influence of Regional-Scale Transport on the Concentrations of Climatically Important Trace Gases at Harvard Forest, Massachusetts

Jennie L. Moody, University of Virginia
Daniel J. Jacob, Harvard University

Objectives: The Harvard Forest atmospheric chemistry site is designed to provide long-term records of the concentrations of climatologically important trace gases in a heavily populated region. Trace gas concentrations monitored at the tower site, five meters above the canopy, include methane and non-methane hydrocarbons, CO, CO₂, O₃, NO, NO₂, and NO_y.

The temporal variance in each species concentration record offers unique clues as to the origin and fate of the species, including in particular the role of human influence. Interpreting this variance is, however, a challenging task. Changing meteorology is certainly a major factor contributing to the variance in atmospheric chemical composition, and some of this variability can be accounted for in a quantitative manner. Harvard Forest is influenced by the day-to-day fluctuations in weather patterns which deliver airmasses from different source regions. By filtering these data on the basis of patterns in the regional-scale transport (derived from 3-D back trajectories), we can explain a significant amount of the observed variation in air mass composition.

The primary goal of this project has been to calculate 3-D back trajectories for air parcels advected to the Harvard Forest atmospheric chemistry monitoring site during the period from June 1990-December 1993, and to use these trajectories to address a number of specific objectives: (1) identify distinct patterns of regional-scale transport to the Harvard Forest site, and their relative frequency of occurrence, (2) interpret the high-frequency temporal variance of the chemical data in terms of chemical source regions, (3) define chemical signatures and trace gas ratios for the different air masses advected to the site, and 4) assess the role of transport in determining the seasonal and interannual variations in trace gas concentrations and fluxes.

Products: We have compiled a four-year record (1990-1993) of 3-dimensional back trajectories arriving at the site, along with an archive of

model soundings for the Harvard Forest location which provide a regional-scale measure of the boundary layer height. These meteorological measures have been used to characterize different transport patterns, and the airmasses they deliver. We have built this archive of trajectories at the university of Virginia, and we are making trajectory data and GIF image plots of the midafternoon trajectory for each day available in the Harvard NIGEC data repository. With the support of this project pattern recognition software was developed to use these trajectories and identify the dominant recurring patterns in the regional scale transport, this is the UVA PATH (Patterns in Atmospheric Transport History) model. In collaboration with the Harvard Forest chemists, we have applied this model and have illustrated the role of regional-scale variability in modulating the concentration of climatically important trace gases measured continuously at the site.

Approach: The back trajectories for this project were calculated using the model wind and temperature fields of the National Meteorological Center Nested Grid Model (NMC-NGM). The NGM provides assimilated observations combined with 12-hour forecast fields of high spatial and temporal resolution, and includes dynamically consistent vertical velocities at 10 terrain following σ -levels between the surface and ~400 hPa. Using these model fields, three-dimensional, back trajectories were calculated four times per day at 04, 12, 16 and 20 UTC, beginning at the model defined top of the boundary layer. In addition, a set of low-level trajectories 500 meters above ground level have been generated for summer months, when the modeled boundary layer depth can grow very deep.

Once trajectories were calculated they were used in the PATH model to determine recurring patterns in the regional-scale wind field. This new program identifies transport patterns by identifying suitable locations, or centers, for potential clusters based on properties of the whole set of trajectories, and then classifying each trajectory to that cluster of the nearest

center. For each trajectory, we calculate a distance matrix, with the distance between two trajectories is defined to be a weighted mean of the distances between corresponding endpoints (latitude, longitude and pressure) over the length of the two trajectories. Each trajectory is considered in turn as a potential center and ranked according to how well it satisfies our criteria: 1) two trajectories within the same cluster should represent similar transport, 2) trajectories from different clusters should represent distinctly different transport, and finally, 3) all of the clusters chosen should be significant and representative of the data set, that is, anomalous or small, statistically insignificant sets of trajectories should not be considered clusters.

Non-parametric statistical test have been used to compare the distributions of chemical concentrations across different transport pattern categories. In this manner we have performed analyses of variance to characterize the amount of variability in air mass composition which can be explained by regional-scale motion.

Results to Date: We have applied the Patterns in Atmospheric Transport History (PATH) model to the set of all daytime trajectories (12, 16, and 20UTC starting times) for the entire period from January 1990 through December 1993 to characterize regional scale transport patterns for the Harvard Forest site. Acknowledging the significant seasonal differences in atmospheric chemistry, we have analyzed results for two broad seasons, the cool season (win) runs from October-March, while the warm season (sum) runs from April through September. Figure 1 illustrates the resulting probability distributions, these show the relative likelihood of air parcels advected to Harvard Forest having passed over upwind locations. This display is based on the trajectories being represented as 2-dimensional probability distributions (Samson and Moody, 1981). From this figure it is apparent that the condition of low-wind "local" conditions, and "Anticyclonic" flow around a relatively stationary high pressure occur most frequently in the warm months, while "NW rapid" transport, and the relatively high speed transport from the "W" occur most frequently in the cool months. Table 1 shows the average chemical composition using the observations corresponding to the time of each trajectory grouped into a transport pattern. Together these results illustrate that the most polluted conditions at Harvard Forest occur under conditions of "local" flow, and under regional-

scale transport from the midwest during the warm season months. High O₃ and CO and NO_x occur together in the "local" flow conditions, while the "W flow" in the warm season has lower NO_x concentrations, and a higher NO_y/NO_x ratio (not shown) indicating aged air masses. By contrast, in the cool months, the highest average O₃ concentrations are delivered under "N" and "NW-rapid" flow conditions, with the lowest average CO and NO_x concentrations, suggesting an influence of natural sources. The "local flow" conditions and "SW" flow deliver the highest average CO and NO_x concentrations, indicating the influence of east coast sources. While these differences in composition among transport patterns are statistically significant an analysis of variance indicates that differences in air mass source region explains 10-20% of the variance in chemical composition. Therefore we need to look within these transport patterns to identify other factors which influence chemistry. One of these is the time of day (we know that these chemical species show temporal variation throughout the day). Another factor to consider is the depth of the mixed layer, which we have characterized on a regional-scale using the NGM data. We will continue in an effort to determine the influence of these additional factors on the chemical composition (including hydrocarbon levels) of the Harvard Forest atmosphere. To date, we have accomplished objectives 1 through 3, we will go on to investigate interannual differences in transport patterns, as discussed in objective 4.

References:

Samson, P.J. and J.L. Moody, Backward trajectories as two-dimensional probability fields, in *Air Pollution Modeling and its Applications: I*, edited by C. De Wispelaere, 43-54, Plenum, New York, 1981.

Manuscripts in preparation:

Modeling Patterns in Atmospheric Transport History: the UVA PATH model, J.L. Moody and J. Newbrough, manuscript in preparation for *J. Applied Meteorology*, 1995.

Harvard Forest Regional-scale Air mass composition by PATH, J.L. Moody, J. W. Munger and D.J. Jacob, manuscript in preparation for *J. Geophysical Research*, 1995.

Student participation: In July of 1993, at the

outset of this project, Jonathan Newbrough, a Master's degree Math candidate, worked on this project (50% effort) under the supervision of the PI, coding the PATH algorithm, and assisting in graphical display development. In September of

1994, Owen R. Cooper, a Master's degree candidate in Environmental Sciences joined the project (25% effort), working with the trajectory model and analyzing chemical composition as a function of model PATH using non-parametric statistical tests.

Figure 1. Harvard Forest flow patterns defined for four years of back trajectories (1990-1993) using the PATH model. Each image depicts the relative probability of transport from upwind regions. The frequency of occurrence of trajectories in each transport PATH by season is noted in each panel. (win: Oct-Mar; sum: Apr-Sep)

Table 1: The chemical composition of each Harvard Forest flow path by season.

PATH	Win O ₃	Win CO	Win NO _x	Sum O ₃	Sum CO	Sum NO _x
local	30	283	10.9	52	214	3.6
NW-slow	31	234	6.8	45	168	2.6
SW	26	287	13.2	45	203	3.7
Anticycl.	35	218	9.1	44	193	3.5
W	29	234	8.5	52	214	2.4
NW-rapid	35	196	4.2	40	146	1.6
N	39	191	3.8	40	146	2.1

Evaluation of Sources and Sinks for Greenhouse and Ozone-Depleting Gases in Rural New England: A Prelude for Mitigation

Michael B. McElroy and Allen H. Goldstein
Harvard University

James W. Elkins
National Oceanic and Atmospheric Administration

Objectives: This research is directed at locating and quantifying the sources and sinks of chemically and/or radiatively important trace gases, including C2-C6 hydrocarbons, chlorofluorocarbons, chlorinated hydrocarbons, nitrous oxide, sulfur hexafluoride, methane, and carbon monoxide in the Northeastern United States. The objectives can be separated into two general areas: 1) Measuring biogenic emissions and determining their response to climate forcing (temperature, sunlight, season) and 2) creating a data base defining background concentrations, seasonal cycles, interannual variability, and anthropogenic sources, for more than 30 trace gases.

Products:

- 1) The Forest and Atmosphere Chromatograph for Trace Species (FACTS), described below, has been constructed and can measure 14 CFC's and greenhouse gases at twelve minute intervals. FACTS will be deployed at Harvard Forest during the summer of 1995.
- 2) Hydrocarbon data have been collected continuously since July 1992 at 45 minute intervals [Goldstein et al., 1995a]. The data record includes 80% of all possible time intervals for three years.
- 3) Seasonal cycles of anthropogenically emitted hydrocarbons have been analyzed using a 3 dimensional global chemical tracer model to provide new information on midlatitude concentrations of OH [Goldstein et al., 1995b].
- 4) Whole ecosystem biogenic emission rates of ethene, propene, and 1-butene from a forested environment have been quantified and compared to regional anthropogenic emissions and global emission estimates [Goldstein et al., 1994].

Approach: Continuous measurements of trace gases have been made by professor Steve

Wofsy's research group at Harvard Forest since 1990 including H₂O, CO₂, NO, NO₂, NO_y, CO, and O₃. Non-methane hydrocarbon (NMHC) measurements were added in July 1992, using an automated gas chromatograph equipped with dual flame ionization detectors [Goldstein et al., 1995a]; results are summarized below. The FACTS instrument will be deployed in summer 1995, enhancing existing capabilities to include nitrous oxide (N₂O), sulfur hexafluoride (SF₆), chlorofluorocarbons (CFC's) -11, -12, -113, halon-1211, chloroform (CHCl₃), methyl chloroform (CH₃CCl₃), trichloroethylene (C₂HCl₃), perchloroethylene (C₂Cl₄), carbon tetrachloride (CCl₄), methane (CH₄), hydrogen (H₂), and carbon monoxide (CO). FACTS is equipped with four separate chromatography channels coupled to electron capture detectors (ECDs).

Simultaneous measurement of a suite of gases provides information on common sources and relevant source strengths. For example, measurements on a particular air mass indicating simultaneously high concentrations of acetylene and CFC's can be interpreted as evidence that the air mass had passed recently over an urban environment, and the relative source strengths for emissions in this environment can be deduced. Measurements of elevated CH₄ in the absence of elevated CFC's might identify air that received a significant input of gas from a near-by land-fill.

Harvard Forest is ideally located near landfills, sewage treatment plants, and agriculture, and is downwind of a major industrial center (New York City). Measurements for this array of species will allow us to distinguish between the many anthropogenic and natural processes which release radiatively and chemically active gases, including those of the forest itself. Measurements, such as these, in close proximity to continental sources are urgently required to complement data from the remote sites emphasized in the NOAA/CMDL (National Oceanic and Atmospheric Administration/Climate

Monitoring and Diagnostics Laboratory) global network. Information obtained in the study should allow definition and assessment of the significance of particular sources, contributing to the development of cost-effective strategies for mitigation.

Results to Date:

1) Forest and Atmosphere Chromatograph for Trace Species (FACTS):

This instrument measures 14 trace gases every 12 minutes. Identical systems are planned for installation at the NOAA/CMDL stations located at South Pole, American Samoa, Mauna Loa, Hawaii, Niwot Ridge, Colorado, and Barrow, Alaska. The instrument comprises four separate gas chromatographic channels (Figure 1) each incorporating an electron capture detector (ECD) and columns measuring the following combination of species (precision given in brackets): (channel 1) H_2 (0.95%), CH_4 (0.17%), and CO (1.5%); (channel 2) CFC-12 (0.18%), CFC-1211 (2.0%), CFC-11 (0.14%), and CFC-113 (0.93%); (channel 3) CFC-11 (0.14%), CFC-113 (0.72%), $CHCl_3$ (5.5%), CH_3CCl_3 (0.25%), CCl_4 (0.16%), C_2HCl_3 (NA), and C_2Cl_4 (1.1%); and (channel 4) N_2O (0.40%) and SF_6 (1.65%). Samples ($2-10\text{ cm}^3$) are injected by a two-position, 10-port gas sampling valve (GSV) onto two separation columns, a main column and a pre-column. Samples and a calibrated standard are alternated by switching the stream selection valve (SSV). Diana Barnes, a fourth-year graduate student in the Department, has constructed the FACTS instrument which was designed and built at NOAA/CMDL in Dr. Elkins' laboratory. She will deploy FACTS in summer 1995 and maintain the measurement program. NOAA/CMDL will provide accurate gravimetric gas standards for the FACTS system.

2) Whole-ecosystem emission rates for ethene, propene, and 1-butene from Harvard Forest were determined for January through December 1993 [Goldstein et al., 1994]. Emissions were calculated using a micrometeorological technique where exchange coefficients (K) determined from observed CO_2 fluxes and gradients were multiplied by the observed hydrocarbon gradients. Average emissions of ethene, propene, and 1-butene during summer were 2.63, 1.13, and $0.41 \times 10^{10}\text{ molec/cm}^2/\text{s}$ respectively. Emission of these olefins were correlated with incident solar radiation and were zero at night (Figure 2), implying a source

associated with photosynthesis. Comparison of our measurements with a model of anthropogenic sources (NAPAP, 1985) suggests that emissions of propene and 1-butene by vegetation during summer exceed anthropogenic emissions in the northeastern United States, and emissions of ethene by vegetation contribute about 50% of anthropogenic sources. During winter, we observed dominant contributions from anthropogenic sources, and the NAPAP (1985) inventory accurately predicted observed emission ratios. We have argued that terrestrial vegetation could provide the dominant global source for two important reactive olefins, propene and 1-butene, and that terrestrial biogenic emissions of C_2-C_4 olefins may be significant for atmospheric photochemistry.

3) The seasonality and annual mean concentration of OH in northern midlatitudes was elucidated from two years of non-methane hydrocarbon measurement (August 1992 through July 1994) (e.g. Figure 3) and comparison with model results [Goldstein et al., 1995b]. The seasonal cycle of background concentrations for alkanes with predominantly anthropogenic sources (ethane, propane, butane, isobutane, pentane, hexane) and acetylene, could be cleanly extracted from the ~900 measurements each month at this rural site despite its proximity to an industrialized region (Figure 4). Background concentrations exhibited seasonal maxima in winter and minima in summer. The phase of the seasonal cycle for each species reflected its rate of reaction with OH: the faster the reaction, the earlier the peak in winter and the more rapid the decline in spring. Hydrocarbon background seasonal cycles observed at Harvard Forest are regulated by balance between nearly aseasonal anthropogenic emissions and chemical loss by reaction with OH. The amplitude of the annual cycle for ethane background, relative to the annual mean, is a measure of absolute OH concentrations, while relative variations of species with lifetimes shorter than that of propane are sensitive only to the ratio of OH in different seasons. Winter:summer ratios for isobutane, butane, and pentane were similar, implying a summer:winter ratio for OH of 9 ± 2 at northern midlatitudes. The annual cycle for ethane provided a measure of the mass-weighted annual mean OH concentration at northern midlatitudes, $7 (\pm 3.5) \times 10^5\text{ cm}^3$, as simulated using a 3-dimensional chemical tracer model.

4) The non-methane hydrocarbon instrument was modified in spring 1995 to allow quantitative measurements of isoprene concentrations and gradients. Previously, loss of isoprene had occurred in the stainless steel cryogenic preconcentration system and transfer lines. Isoprene loss was eliminated by installing stainless steel tubing coated with deactivated fused silica (SILCOSTEEL). Whole ecosystem isoprene emissions have been measured since June 1995. Leaf level isoprene emissions were measured in July 1995 at Harvard Forest by Russ Monson (University of Colorado), Manuel Lerdau (SUNY Stonybrook), and Tom Sharkey (University of Wisconsin). The goals of this collaborative project include the intercomparison of leaf level measurement techniques, understanding how leaf level emissions can be scaled and extrapolated to whole ecosystem emissions, and developing a database to test isoprene emission models.

Students: Diana Barnes - graduate student;
Claire Monteleoni - undergraduate student

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Figure 1 - FACTS schematic for a single channel.

Figure 2 - Average diurnal cycles for fluxes of ethene, propene, and 1-butene along with temperature and incident photosynthetically active radiation (PAR) (June 1 to October 31, 1993). Data was parsed into two hour time windows.

Figure 3 - Ethane and Acetylene concentrations measured at 45 minute intervals above Harvard Forest from August 1992 to July 1994. A line is drawn through the running 0.1 quantile of the data in 30 day intervals, identifying the seasonally changing background concentration.

Figure 4 - Background concentrations from August 1992 to July 1994 defined as the running 0.1 quantile of the data in 30 day intervals for (a) ethane, acetylene, propane, and butane, and (b) isobutane, pentane, hexane, and propene.

Schumann Resonance Measurements as a Sensitive Diagnostic for Global Change

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Objectives: Monitor and study changes in global lightning activity with Schumann resonance (SR) measurements on time scales ranging from the diurnal to the interannual as a diagnostic for temperature change.

Products

- Continuous measurements of Schumann resonance spectra in both the electric and magnetic field in West Greenwich, Rhode Island, Nov. '93–present
- Magnetic spectra for Fishers Island, New York, for selected periods
- Computations of global mean potential temperature and wet bulb potential temperature
- An inversion method and results for the diurnal variation of vertical moment change associated with global lightning activity on selected days (Heckman and Williams, 1995)
- TOVS satellite observations of global deep convection on the seasonal time scale (Williams et al., 1995)
- Analyzed Schumann resonance transients associated with mesospheric 'sprites' (Boccippio et al., 1995)
- Analysis of upper level cirrus on a global scale and documented correlation with surface air temperature (Kent et al., 1995)

Approach: The Earth's Schumann resonances provide a natural and inexpensive framework for global studies. A complete set of calibrated electromagnetic field components in the Schumann resonance band (3–120 Hz) are now continuously recorded in West Greenwich, Rhode Island. Power spectra are continuously archived; time series may be recorded as required for more detailed studies of large transients that "ring" the entire earth-ionosphere cavity. Comparisons with other global climate variables (wet bulb potential temperature, deep convection and upper level cirrus) have been investigated.

Results:

Comparisons of Schumann Resonance Signals at Distant Sites: To establish the global nature of the magnetic signals measured

in West Greenwich, Rhode Island, we have taken advantage of ELF facilities of the Naval Underwater Warfare Center in New London, Connecticut. Two-component magnetic signals in the band 3–30 Hz have been recorded for extended periods on Fisher's Island, New York (an island off the Connecticut coast at New London), approximately 45 km from the West Greenwich station, with recording equipment identical with that used in Rhode Island. This distance is a tiny fraction of a SR wavelength, and so the global SR signal should be essentially identical at the two sites. In contrast, the local noise in the ELF band is expected to be quite different at the two sites. A comparison of the diurnal variation of $H_x^2 + H_y^2$, the total power in the horizontal magnetic field, for a sample day in Figure 1 for the two sites, shows strong evidence that the global signal is dominant. These diurnal variations show a minimum for the most distant Asian source at 8Z. The African source peaks at 16Z and the South American source near 20Z. It is noteworthy that correlated measurements of the DC global circuit on individual days at distant sites are seldom if ever achieved, primarily because of the local noise present in the atmospheric boundary layer. The SR signals, which are not dependent on the local air conductivity, are immune from this local variability.

One original goal of the NIGEC studies was to establish absolute calibration so that signal levels in the 1990's could be compared with levels in the 1970's, as documented earlier in Williams (1992). The independently calibrated signals in Figure 1 and for many other days show agreement at the 1 dB level, but Polk's earlier measurements (*Geophysics and Space Data Bulletin*, AFCRL) at the same (West Greenwich) location show mean values which are higher by 5–10 dB, with a mean amplitude of 2.3 pT/. The reason for this discrepancy remains unresolved.

Inversion of Single-Station Measurements for Regional Source Strength: Our original NIGEC proposal outlined a theoretical attack on the inverse problem for SR: Given measurements of

power spectral density in the electric and magnetic field, solve for the global distribution of lightning sources that produces these powers (Williams et al., 1994). The initial efforts allowed both source position and strength to vary (Blasch, 1994), but this proved to be too loosely constrained and the (nonlinear) inversions were found to be unstable. Recently we have explored a large number of trial sources whose positions are fixed and then solve for source amplitudes which match the observed power spectral density in a least squares sense. This is a linear problem. The framework is analytic and makes use of the traditional isotropic normal mode model which was used successfully for SR point sources otherwise known as Q-bursts (Kemp and Jones, 1970). Figure 2 from Williams (1994) shows an example of an observed spectrum in West Greenwich which is input to the inversion. The FFT's are updated every 6 minutes and so this is the limiting resolution in measuring the lightning source distribution on the planet. Figure 2 shows the results of an inversion for a 24 hour period of observations. In this case, four dominant lightning source positions were assumed, Asia, Africa, America and the Central Pacific. Compelling evidence for the success of the inversion with single station observations is the space-time evolution of the source regions which is consistent with traditional analysis (Whipple, 1929). Asia is warmed by the sun and brightens at 9Z followed in turn by Africa at 15Z and South America at 21Z. The Central Pacific source is not given large weight, at least relative to Africa and South America, consistent with other observations of reduced lightning over the cooler oceans. An absolute measure of source strength (the vertical moment change) is obtained for each of the four regions over 24 hours. Thus single station data provide substantially more information on global electrical activity than DC circuit measurements which are only scalar rather than vector measurements.

Seasonal and Interannual Variations in SR Intensity: To examine the variation of SR amplitude on longer time scales, continuous recordings of electric and magnetic spectra are still underway. The record in West Greenwich now extends from November 1993 to present. More than 300,000 Lorentzian fits of spectra have resulted in records of total magnetic power for each of several resonant modes. The monthly mean results for the 2nd mode (14Z) are shown in Figure 3. This record shows the increase from winter 1993-94 to summer 1994

and, as predicted in the previous NIGEC report (Williams, 1994), a return to lower values in winter 1995. This pronounced annual cycle is in phase with the seasonal variation of global temperature, usually ascribed to the greater continentality of the Northern Hemisphere than Southern Hemisphere (Williams, 1994). The standard deviations in Figure 3 represent the global diurnal variations which are comparable to the seasonal variations.

One puzzle remains. The semiannual signal in the record of Figure 3 (and in Figure 3 of Williams, 1994) is weak in comparison with the annual signal. This is peculiar given the evidence that the latitudinal distribution of total lightning is maximum in the equatorial region (Williams, 1992) and the climatological temperature variation in the tropics is largely semiannual (Williams, 1994). Also, recent analyses of TOVS IR data shows a pronounced semiannual signal in deep convection in the tropics (Klatsky et al., 1994; Williams et al., 1995), with peaks in April and October. This apparent discrepancy led us to examine the dominant lightning source for SR.

Consider the hypothesis that cloud-to-ground lightning dominates the Schumann resonance signal. Recent studies (Williams et al., 1995) show that the peak currents and the vertical dipole moment changes for ground flashes are substantially larger than for intracloud flashes. Furthermore, a recent collection of observations of ground flash density at four low latitude sites with common recording equipment (Table 1) strongly suggests that ground flash activity has a local minimum in the near equatorial zone, in contrast with the behavior of total lightning. These results may provide an explanation for the weak semiannual signal in the observations of Figure 3. The record in Figure 3 is too short to say much about interannual variability. There is no question, however, that the (calibrated) signal amplitude in specific months in 1995 has not increased substantially relative to 1994. Based on earlier arguments that amplitude should increase with temperature (Williams, 1992; 1994), we see no global warming trend in our measurements.

Sprites, ELF Transients and Positive Ground Strokes: An important side benefit of the reactivated measurement site in Rhode Island on this project was the discovery of a connection between mesospheric lightning (sprites) and the

transient excitation of the entire earth-ionosphere cavity. Positive ground flashes are the strongest single contributor to the SR transient excitation and have been found to be coincident with red sprites at altitudes of 70–90 km over large mesoscale convective complexes a few thousand kilometers from the Rhode Island site. This work was recently accepted for publication in *Science* (Boccippio et al., 1995), where an explanation for sprites is proposed based on the electrostatic field change by the positive ground discharge which stresses the mesosphere to breakdown in a glow type discharge. The tie-in with SR and the existence of an apparent threshold in peak current make it possible to obtain a global climatology of sprite occurrence from single station observations. Work in this direction is underway.

Comparisons of the Behavior of SR Amplitude and Ionospheric Potential: During May 1995, Earle Williams worked with Dr. Ralph Markson and Dr. Lothar Ruhnke on Dr. Markson's project to measure the DC global circuit simultaneously in Massachusetts and in Australia. Detailed comparisons will be made on the diurnal time scale with simultaneous recordings in West Greenwich. The analysis of these measurements is in progress.

Conference on Schumann Resonances: At the recent XXI Assembly of the IUGG meeting in Boulder, Colorado in July, a majority of international SR researchers assembled for discussion on theoretical models for SR and the interpretation of ongoing global measurements with these models. Earle Williams organized and chaired this meeting.

Student and Other Participants

Dennis Boccippio—Graduate student in Earth, Atmospheric, and Planetary Sciences (EAPS). Dennis coordinated and analyzed the observations which link sprites and Schumann resonances. He has continued with analyses of global wet bulb potential temperature.

Robert Boldi—Former graduate student in EAPS and currently a full time employee at Lincoln Laboratory. Bob developed all data acquisition and data processing capability for SR and has provided spectral fits to all data.

Carmine di Chiara—Undergraduate student in Electrical Engineering. Carmine analyzed

simultaneous observations from Fisher's Island and West Greenwich on an MIT UROP (Undergraduate Research Project).

Stan Heckman—Former graduate student in EAPS and currently an employee at Phillips Laboratory. Stan developed the inversion program and integrated the observations for obtaining global lightning sources.

Charles Wong—Graduate student in the MIT Electrical Engineering Department. Charles is working on methods for automated detection of global locations for SR transients and for single-station counting of the global flash rate at ELF.

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Figure 2. Results of an inversion of single station SR data from West Greenwich, RI for lightning source strength in Asia, Africa, America and the Central Pacific Ocean.

Figure 1. Comparison of diurnal variation of total magnetic power ($H_x^2 + H_y^2$) in West Greenwich, RI and Fisher's Island, NY on November 5, 1994.

Figure 3. Total magnetic power in the 2nd resonance (14Hz) for West Greenwich, RI from December 1993–May 1995. Monthly mean values are taken. The standard deviation provides a measure of the diurnal variation rather than an uncertainty in the measurement.

Long-Term, Whole-Ecosystem Observations of Atmosphere-Biosphere Exchange in a Mid-Latitude Forest

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Song-miao Fan, and Bruce C. Daube
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Objectives

CO₂ Our objectives are to continue ongoing measurements of net CO₂ exchange at Harvard Forest for three years, and to add new measurements to characterize the forest environment. The goal is to define the response of northern forests to climate variations on seasonal and annual time scales, in order to help predict future shifts in carbon storage in northern forests associated with variations in climate.

NO_x and NO_y We propose to continue measuring net exchanges of NO_y and O₃ and to perform comprehensive analysis of the long data records to define the effects of nutrient and pollutant inputs on carbon uptake.

Approach: During the first four years of this study we developed the methodology, determined baseline mean rates for net uptake of CO₂ and deposition of O₃ and NO_y, and defined interannual variations of the annual carbon balance. We have formulated hypotheses to explain year-to-year anomalies in carbon storage which we will test during the next observation period. Each year has revealed new factors influencing carbon storage and we expect additional new information from future natural "experiments". We are continuing the observations and intensively analyzing the results to obtain better understanding of the rates for, and interactions among, key processes regulating net carbon storage in forests and the role of forests in the regional and global budgets for NO_x and other reactive species.

Products: The major product of the studies to date has been the demonstration that long-term eddy correlation flux measurements can be applied to address a wide range of important regional and global problems of atmosphere-biosphere exchange, for time scales spanning hours to many years. Plans are in progress that would develop a large number of study sites following this model.

Other important products include definition of the net uptake rates for CO₂ and NO_y, new information on the importance of wintertime deposition and respiration in annual net exchange budgets, and definition of the mean concentrations and seasonal variations of OH radicals in northern midlatitudes.

Summary of recent results

CO₂: Four years of measurements of Net Ecosystem Exchange (NEE) for CO₂ are shown in Figure 1. The observations span a variety of climate conditions, allowing quantitative assessment of the physical and biological controls on whole-forest activity. We have focused in the past year on assessing the mechanisms for ecosystem changes in gross ecosystem production (GEP) and respiration (R), by disaggregating the eddy-correlation measurements of NEE (Goulden et al, 1995a), and also we completed a detailed evaluation of the accuracy and precision of the measurements on both short and long time scales (Goulden et al, 1995b).

Annual GEP ranges from -11.1 to -12.4 metric tonnes of C ha⁻¹ and R from 9.1 to 10.7 t C ha⁻¹ (Table 1). Variations in R and GEP tended to offset one another on an annual time scale, and annual NEP ranged from -1.8 to -2.5 t C ha⁻¹. Annual variations could be traced to short anomalous periods that occurred most often in spring, and did not correlate well with variations in annual mean climatic parameters. We infer that efforts to predict current and future carbon balance of the biosphere must consider seasonal patterns of climate change. The observations indicated that quantity and timing of snowfall, and the time of development of the canopy, were the most important parameters associated with variance of rates for CO₂ uptake in 1990-1994.

NO_x and NO_y: We have obtained a five-year data set for concentrations and fluxes of nitrogen

oxides and ozone at Harvard Forest in central Massachusetts, and for one summer at Schefferville in sub-arctic Quebec. The results may be summarized as follows:

- 1) Long-term eddy correlation flux measurements for NO_y are feasible.
- 2) Horizontal transport from source regions, chemical reaction, and vertical mixing control dry deposition of NO_y to forest canopies. In contrast to the observations for O_3 deposition, NO_y deposition fluxes were insensitive to changes in either leaf area or stomatal conductance.
- 3) The net NO_y flux was from the atmosphere to the canopy at both Harvard Forest and Schefferville. Soil emissions of NO were measurable, but small. Mean mid-day values of net dry NO_y flux from atmosphere to canopy were 3.4 and $3.2 \text{ mmol m}^{-2}\text{hr}^{-1}$ at Harvard Forest in summer and winter, respectively, and $0.5 \text{ mmol m}^{-2}\text{hr}^{-1}$ at Schefferville during summer. Nighttime values were 1.3 , 2.0 , and $0.15 \text{ mmol m}^{-2}\text{hr}^{-1}$, respectively.
- 4) Total annual deposition of NO_y by wet and dry processes at Harvard Forest averaged $44.5 \text{ mmol m}^{-2}\text{yr}^{-1}$ for the period 1990-1994. There was relatively little variation from year-to-year, but the partitioning between wet and dry varied significantly (Figure 2).

The role of deposition and horizontal transport was demonstrated by differences between wind sectors at Harvard Forest and by the contrast between the rural site at Harvard Forest and remote site at Schefferville. Mean concentrations of NO_x and NO_y and deposition fluxes of NO_y were about twice as high at Harvard Forest when the wind was from the SW than from the NW. SW winds transport pollutants from major urban areas and are associated with regional stagnation events; NW winds which pass over fewer pollution source regions. Concentrations of NO_x and NO_y at Schefferville were a factor of 10 less and NO_y deposition fluxes were a factor of 5 less than the summertime mean values for clean sector winds at Harvard Forest (Figure 3).

Seasonal changes in OH concentrations at mid latitudes lead to a 10-fold decrease in rates for homogeneous oxidation of NO_x to HNO_3 . However, total deposition of nitrate decreases by only a factor of 2 while background levels of NO_y

are nearly constant. Evidently the supply of HNO_3 or other depositable species does not decrease in proportion with OH concentrations. We estimate that nocturnal heterogeneous production of nitrate contributes 25-40% to the daily NO_y dry deposition (Figure 4) in summer, even though daytime OH concentrations reach seasonal maximum values. We infer that heterogeneous reactions (e.g., $\text{N}_2\text{O}_5 + \text{H}_2\text{O}(\text{aerosol}) \rightarrow 2\text{HNO}_3(\text{aerosol})$) must be important in both summer and winter.

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Generalizing the Core Experiment Work at Harvard Forest to Address Global Change Issues Through Mechanistic Modeling of Forest Metabolism

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Objectives: An important test of our mechanistic understanding of forest metabolism is to construct a numerical model of forest mass and energy exchange, including canopy physiology, tree growth, soil physics, and soil biology, and then to compare the output of that model to the independent and integrative tower-based field measurements of mass, energy, and momentum exchange currently being made at the Harvard Forest. The objectives of this project are to develop a forest canopy model and a soil model that can be compared with the ongoing tower measurements.

Products: This project will produce detailed quantitative models of mass, energy, and momentum exchange by a forest ecosystem. The canopy model will also simulate tree growth and intra-ecosystem cycling and storage of carbon, water, and nitrogen. The soil model will include microbial decomposition and gaseous

diffusion within the soil.

Approach: For the canopy model, we have developed individual process models as FORTRAN subroutines and have combined the subroutines into one overall program for the purposes of simulating ecosystem physiology. The model includes subroutines that predict canopy mass, energy (radiation, sensible heat, and latent heat), and momentum exchange, leaf phenology, leaf, stem (branch and bole), root growth, and aboveground and belowground litter production. The individual modules have been tested in isolation from the rest of the model so that we can ascertain the strengths and weaknesses of the individual components. The canopy model inputs include variables that are being measured at Harvard Forest and that are available for other research sites, including air temperature, humidity, wind speed, solar irradiance, CO₂ concentration, and precipitation.

The complete model has been tested with measurements of mass, energy, and momentum exchange being made by the eddy correlation method in the core experiments at Harvard Forest.

The soil model contains algorithms that relate microbial decomposition to temperature and water content of the soil at each of four horizons (O, A, B, and C). Effective diffusivity of gases is calculated from estimates of total porosity and soil water content. Fluxes of CO₂ between soil horizons are estimated from concentration gradients and diffusivity estimates. The CO₂ concentrations are recalculated at one minute time steps to account for the interaction of CO₂ production and transport.

New field data are also being collected in order to provide data to parameterize and test the soil model. Existing Harvard Forest datasets on soil respiration, soil temperature, and soil moisture are too erratic and incomplete for this purpose. Four soil pits have been instrumented with gas sampling tubes, thermocouples and TDR probes (for soil moisture measurements) in each horizon. Two pits are in well drained soils and two in poorly drained soils, all within the tower footprint. Weekly measurements of soil respiration were begun in the autumn of 1994, resumed in the summer of 1995 and are ongoing.

Results to Date: The canopy physics and physiology model has been completed. Canopy model predictions are in good agreement with the independent field measurements. These data were presented in last year's progress report and are also published (Amthor et al., 1994).

The soils model has been coded and debugged, but lack of good field data has precluded testing of the model. We now have data from August to December, 1994, and from June onward in 1995 for soil respiration and for profiles of soil CO₂, temperature and moisture content. Preliminary results show that, as expected, poorly drained soils that remain wetter than well-drained soils also have lower soil respiration rates (Figs. 1 and 2). Decomposition is slower in poorly drained soils, presumably due to lack of oxygen, and relatively deep organic horizons have developed. The poorly drained soils also have higher CO₂ concentrations within the soil profile, but lower diffusivities result in lower CO₂ fluxes. Because

the poorly drained soils are close to the tower in the SW, but far from the tower to the NW, this result has important implications for the observation that wind direction affects the net CO₂ uptake rates measured at the tower. Differences in soil storage of C along landscape drainage gradients may account for part of the difference in net ecosystem productivity observed with wind direction, and soils may be an important component of net ecosystem uptake of atmospheric C.

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Amthor J.S. 1994. Testing a mechanistic model of Harvard Forest ecosystem physiology. Presented at Harvard Forest Symposium April 1994 in Petersham, MA.

Student Participation: Ilse Ackerman (Antioch College): 100% time as a NIGEC summer intern during the summer of 1994 and also as a Woods Hole Research Center intern during the autumn of 1994. Jesse Reynolds (Hampshire College): 100% time as a NIGEC summer intern in summer of 1995.

Figure 1. Mean volumetric water content of the top 15 cm of O and A horizon during the period June 1 - July 15, 1995. Each bar is a mean of three TDR measurements at each site and each date, averaged over 6 weeks. The sites are arrayed along transects to the SW and NW of the tower. To the SW, the near (N) site is poorly drained, the mid (M) site is moderately well drained, and the far (F) site is well drained. To the NW, the sequence is reversed.

Figure 2. Soil respiration measured using soil chambers during the period June 1 - July 15, 1995. Each bar is a mean of six flux measurements at each site and each date, averaged over 6 weeks. Note that in each compass direction, the wetter, poorly drained soils (c.f. Fig. 1) have the lowest respiration, while the well drained soils (SW-F and NW-N) have the highest respiration.

Biological and Physical Controls on Soil Organic Matter Quality and Quantity

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Objectives: Soils contain a large fraction of carbon in the terrestrial biosphere and are a major source of atmospheric carbon dioxide (CO₂). Though the importance of soils to the global carbon cycle is clear, there is little quantitative information on rates of soil organic matter accumulation, potential for increased soil carbon storage, and the controls regulating soil organic matter sequestration and soil respiration. The objectives of this study are to (1) quantify the relative contributions of above- and belowground plant inputs to organic carbon and

nutrient storage in forest soil, (2) evaluate the roles of above- and belowground litter in controlling soil biological activity and soil organic matter dynamics in forests, and (3) quantify the importance of forest litter inputs (above- plus belowground) in contributing to the recovery of biogeochemical cycling in impoverished soils. To meet these objectives we are utilizing long-term litter manipulation plots, established at the Harvard Forest in 1990-1991, that include the following treatments:

Control	(normal litter inputs)
No litter	(aboveground litter excluded from plots)
No roots	(roots excluded from plots by trenching and barriers)
No inputs	(no aboveground litter and no roots)
Double litter	(twice aboveground litter)
O/A-less	(Organic and A horizons replaced with B horizon soil)

Treatments have been maintained since their initiation.

Products: (1) Soil respiration time course by day, week, month, and year for all treatments, (2) Assessment of relationship between soil respiration and soil temperature, (3) Delineation of the influence of soil temperature on CO₂ production from root respiration versus organic matter decomposition, (4) Comparison of soda lime technique and IRGA system for measurement of soil respiration, (5) Time course for soil temperature and soil moisture by treatment (6) Assessment of role of leaves versus roots on concentration of dissolved organic carbon (DOC) in soil solution below forest floor and at 60 cm soil depth.

Approach: Soil respiration is measured now with an backpack mounted IRGA system (flow-through chamber), soil moisture by time domain reflectometry (TDR), and soil temperature with automated soil temperature probes. During the 1994 field season we measured soil respiration concurrently with the soda lime technique and

the IRGA system. Daily soil respiration and soil moisture are measured once weekly from June to August and twice monthly in April and May and from September to December. Soil temperature (5 cm and 10 cm soil depths) is collected hourly over the entire year. Soil solution samples for analysis have been collected following major storm events during the summer and at least twice monthly during the spring and fall.

Results to Date: Soil respiration, which continues to vary by treatment, appears more sensitive to temperature on plots with roots (Control, Double Litter, No Inputs) than on plots without roots (No Roots, No Inputs) or with minimal roots (OA-less). The relationship between soil respiration and soil temperature was linear ($R^2 = 0.84$, $p < 0.05$) over the measured soil temperature range of 9-21°C (Fig 1). Slopes for treatments with roots were significantly different and higher than those for treatments without roots or minimal roots. Q_{10} values for the response over the soil temperature range 3-21°C were 2.89 for Control plots, 2.29

for soil organic matter decomposition alone (No Roots), and 3.59 for root plus rhizosphere respiration (Control - No Roots). These results suggest that the sensitivity of soil respiration to soil temperature should be higher when root respiration contributes a larger portion of total soil CO_2 efflux. Comparison of CO_2 efflux as measured by the soda-lime method and IRGA-based system revealed a curvilinear relationship (Fig. 2). Soda lime gave roughly 50% higher values at low flux ($50 \text{ mg CO}_2\text{-C m}^{-2} \text{ hr}^{-1}$) and roughly 50% lower values at the highest measured flux ($300 \text{ mg CO}_2\text{-C m}^{-2} \text{ hr}^{-1}$). The soda lime and the IRGA techniques were in close agreement only when the flux was about $100 \text{ mg CO}_2\text{-C m}^{-2} \text{ hr}^{-1}$.

Soil microclimate varied much less among treatments than we had anticipated. While soil moisture (0-15 cm depth) was much higher on trenched plots (No Roots and No Inputs) at the start of the study, there are no differences in soil moisture among plots except for the OA-less plots (50% less moisture than Control plots on average). Presumably on the trenched plots the absence of water uptake by live roots has been offset by lower water storage associated with lower forest floor mass and lower organic matter in the upper mineral soil. Soil temperature (5 and 15 cm depths) normally varies by 1°C among the treatments. The litter treatments had no discernible effect on DOC concentrations in soil solution. Concentrations below the forest floor ($20\text{--}30 \text{ mg L}^{-1}$) and at the 60 cm depth in the mineral soil ($<2 \text{ mg L}^{-1}$) remained relatively low and did not vary systematically with treatment. The results suggest that interactions between C and N cycles in the soil rather than the quantities of readily decomposable organic matter regulate DOC concentrations.

Manuscripts in preparation and submitted:

Differential responses of roots and soil organic matter to soil temperature, to be submitted to *Nature*.

Comparison of an IRGA-based system and soda-lime as means of measuring soil respiration: results from the litter manipulation plots at the Harvard Forest, Petersham, Massachusetts, USA, to be submitted to *Canadian Journal of Forest Research*.

Presentations:

Biological and physical controls on soil organic matter storage: the DIRT experiment. International Congress of Ecology 1994, Manchester, England.

Biological and physical controls on soil organic matter storage: the Harvard Forest DIRT experiment. Global Change and Terrestrial Ecosystems: the first GCTE Science Conference, Woods Hole, Mass.

Soil respiration relationships at the Harvard Forest litter manipulation (DIRT) plots. 6th Annual Harvard Forest Ecology Symposium, Petersham, Mass.

Figure 1: Relationship between mean daily soil CO_2 efflux and mean daily soil temperature (5 cm depth) by treatment. C = control, 2x = double litter, OA+ = replacement of organic and A horizons with B horizon soil, OX = no litter, T = no roots, TOX = no inputs.

Figure 2: Comparison of mean daily soil CO_2 efflux measured by the soda lime and IRGA-based methods.

Dynamic Heat and Moisture Transport and Baroclinic Adjustment

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1. The interaction of the Hadley Regime and the Eddy Regime (Primary research scientist: Edmund Chang).

Objective: To understand how the Hadley regime and mid-latitude baroclinic regime interfaces in order to relate the intensity of the Hadley circulation to heat transport in middle and high latitudes

Approach: To study both analytically and numerically the balance between the creation of p-v gradients at the edge of the Hadley circulation by the Hadley transports and the erosion of these gradients by the baroclinic eddies generated by these gradients.

Results to Date: A mechanistic approach has been used to investigate the extratropical transient eddies and mean flow response to tropical zonal mean wind acceleration in order to obtain a better understanding of the interaction between the Hadley circulation and the mid-latitude baroclinic eddy regime. An oscillatory source of zonal momentum forcing is applied within the tropical upper troposphere in an idealized global circulation model. No anomalous forcing is imposed outside of the tropics. The mean flow and eddy response, and details of the angular momentum and heat budgets are examined for forcings with different periods.

For low frequency forcing with periods longer than 100 days, the mean flow response is a north/south oscillation of the mid-latitude jet. Examination of the angular momentum budget shows that within the tropics, the mean flow response directly to the imposed forcing, while in the subtropics, the mean flow response via angular momentum transport by the Hadley circulation. In the extratropics, eddy forcing via eddy vorticity fluxes is the only term that leads the mean flow response, and hence mean flow changes in the extratropics is a response to changes in eddy momentum forcing. For forcing with periods less than 100 days, the poleward penetration of the response stops at the equatorward flank of the mid latitude jet and does not penetrate poleward of the jet core. At

even higher frequencies, the response is local over the region of the forcing within the tropics, without any poleward penetration at all. The results suggest the following scenario. i) The imposed forcing in the Tropics leads directly to zonal wind acceleration in the Tropics. ii) This shifts the critical latitude for eddy absorption equatorward, and eddies penetrate more into the Tropics. This equatorward shift of eddy absorption leads to a shift of zonal wind deceleration due to divergence of eddy momentum fluxes equatorward, leading to (relative) acceleration of zonal wind equatorward of the jet axis. iii) Considering this as a source of forcing of the zonal mean flow, this drives an anomalous MMC that gives rise to deceleration of the zonal flow near the flanks of the acceleration region, leading to deceleration of the flow over the jet core. The combined effect of this acceleration/deceleration couplet leads to an equatorward shift of the jet maximum, which brings the eddy creating region and hence region of momentum flux convergence equatorward, further decelerating the zonal flow towards the poleward flank of the jet. The above three steps scenario is consistent with the three different behaviours of the system in response to varying frequencies of forcing. Additional experiments have been performed to confirm the plausibility of the above scenario. A paper (Chang 1995c) is being prepared from this work to be submitted for publication.

A zonal mean (2-D) version of the model, using parameterizations of eddy heat fluxes and momentum fluxes, is being prepared to study the same problem that was studied using a full 3-D model in Chang (1995a,c). Comparison of the results from the 2-D model with those from the full 3-D model will give us indications on whether those eddy parameterizations are valid and whether we understand the factors that control eddy transports and mixing.

2. Potential Vorticity Redistribution and Climate (Primary research scientist: Richard S. Lindzen)

Objective:

Objective: To examine the implications of potential vorticity mixing in the extratropical troposphere for the temperature structure of the atmosphere and for the structure of both transient eddies (i.e., weather disturbances) and stationary waves (the determinants of regional climate).

Approach: Our *approach* focusses on the use of simple models and data analyses.

Results to Date: Potential vorticity is the fundamental quantity in the dynamics of the atmosphere. It is not only a primary tracer, but its distribution largely determines the distribution of wind and temperature, and the gradients in potential vorticity provide the atmosphere with the 'elasticity' that allows both the stable and unstable waves which constitute both weather disturbances and regional variability in climate. Sun and Lindzen (1994, not supported by DOE) analyzed the observed distribution of potential vorticity which demonstrated the clear distinction between the tropics where convection dominates transport, and surfaces of constant PV are almost vertical, and the extratropical troposphere where baroclinic eddies dominate transport, and surfaces of constant PV tend to lie along isentropic surfaces. The eddies have acted to mix PV along the isentropic surfaces while concentrating gradients of PV along the tropopause. Indeed, as argued by Lindzen (1993), when the tropopause defined by the concentration of PV is sufficiently high, the atmosphere is neutralized with respect to baroclinic instability. Thus, baroclinic transport is likely to be the cause of the extratropical tropopause since the convection essential to traditional radiative-convective adjustment is largely restricted to the tropics. The gradient of PV along isentropes serves to determine the shape of the isentropes themselves subject to the specification of the surface temperature distribution and the temperature distribution at the edge of the tropical Hadley domain. We are currently investigating whether this system can be uniquely closed when the radiative budget is included. Our results thus far indicate that the system is determinate, and that the predicted equator to pole temperature is within 2-4C of the observed distribution. The degree of agreement required that there be an ocean heat flux approximately equal to that inferred for the atmosphere. The sensitivity of our results to the specification of ocean heat flux is somewhat surprising, and is the focus of current efforts on

this aspect of the project.

In the meantime, we have examined the consequences of smoothing PV gradients in the troposphere while concentrating them at the tropopause for a number of problems, including baroclinic instability (Lindzen, 1994a, Harnik and Lindzen, 1995) and response to stationary forcing (Lindzen, 1994b). In the former problem we have considered the Charney problem for an unbounded atmosphere with a stratosphere. We have shown a continuous transition from a Charney-like solution without a short wave cut-off to an Eady-like solution as PV gradients are diminished within the troposphere and concentrated at the tropopause. Profound degrees of smoothing and concentration of P-V are associated with virtually unmeasurable changes in the vertical profiles of wind and temperature. The second problem led to particularly striking results – especially when one recalls that the response to stationary forcing is the major determinant of regional variations in climate. Whether a particular longitude is colder or warmer depends primarily on whether the prevailing winds at that latitude are equatorward or poleward, rather than on the local radiative budget. Figure 2 shows the response (for varying degrees of mixing of PV) per 100m of surface orography as a function of zonal wavenumber at the surface and at 10 km. The large peaks at high wavenumbers are not a matter of concern since the forcing at these large wavenumbers is (on a global basis) much less than 100m. The modest peaks at low wavenumbers are more significant given that the forcing is concentrated at these wavenumbers. Note that at all wavenumbers, the concentration of PV gradients at the tropopause can lead to more than a doubling of response amplitudes. This is simply due to the fact that the concentrated PV gradients at the tropopause lead to strong reflections which automatically increase response magnitudes. The modest peaks at low wavenumbers correspond to conditions where the whole troposphere forms a weakly resonant duct, while the sharp peaks at high wavenumbers correspond to cases where the region of concentrated PV gradients, itself, forms a resonant duct.

The above implies that the ability of a model to simulate regional variations in climate depends critically on its ability to simulate accurately the mixing of PV by transient eddies, and on its ability to resolve the concentrated gradients at

the tropopause. Lindzen 1994b shows that numerical smoothing on concentrated gradients has almost exactly analogous effects on calculated response to actual reduced concentrations. It is estimated that vertical resolutions as fine as 1 km may still be inadequate.

We are currently examining (in cooperation with Arthur Hou at NASA) the implications of PV mixing for the extratropical response to El Niño. The nature of the hypothesized relation is described in Lindzen (1994c).

Figure 1.

Figure 2.

Papers resulting from this work:

Chang, E.K.M., 1995a: The influence of Hadley circulation intensity changes on Extratropical climate in an idealized model. *J. Atmos. Sci.*, 52, 2006-2024.

Chang, E.K.M., 1995b: Mean meridional circulation driven by eddy forcings of different time scales. Accepted for publication in *J. Atmos. Sci.*

Chang, E.K.M., 1995c: Extratropical eddy-mean flow interactions induced by zonal wind acceleration in the tropics. In preparation.

Harnik, N. And R.S. Lindzen, 1995: The evolution of the Charney Problem into the Eady Problem as potential vorticity gradients are concentrated at the tropopause. In preparation.

Kirk-Davidoff, D.B., 1995: A study of moist convective instability in the tropics. In preparation.

Lindzen, R.S., 1994a: The Eady Problem with zero PV gradient but beta unequal to zero. *J. Atmos. Sci.*, 51, 3221-3226.

Lindzen, R.S., 1994b: The effect of concentrated PV gradients on stationary waves. *J. Atmos. Sci.*, 51, 3455-3466.

Lindzen, R.S., 1994c: Classic problems revisited. pp 90-98 in *The Life Cycles of Extratropical Cyclones*, Volume 1 (Grønås, S. and M. Shapiro, Editors), Geophysical Institute, University of Bergen, Bergen, Norway 286 p.

Lindzen, R.S., 1995: The importance and nature of the water vapor budget in nature and models. *Proceedings of NATO Workshop on Model Parameterizations*, H. Le Treut (editor), Springer-Verlag, Heidelberg.

Lindzen, R.S., B. Kirtman, D. Kirk-Davidoff and E. Schneider, 1995: Seasonal surrogate for climate. *J. Cli.*, 8, 1681-1684.

Presentations:

Chang, E.K.M., 1994: The influence of Hadley circulation intensity changes on extratropical climate. *Proc. of the 19th Annual Climate Diagnostics Workshop*, Nov. 14-18, 1994. pp. 22-25.

Chang, E.K.M., 1995: Mean meridional circulation driven by eddy forcings of different time scales. 10th Conference on Atmospheric and Oceanic Waves and Stability, June 5-9, 1995. Preprint volume, p. 170.

Lindzen, R.S., 1995: Potential Vorticity mixing and the general circulation (invited lecture). 10th Conference on Atmospheric and Oceanic Waves and Stability, June 5-9, 1995.

Lindzen, R.S., 1995: Potential Vorticity mixing and the general circulation. Institute for Geophysics, University of Oslo, May 2, 1995.

The Composition of Air in the Firn Layer of Ice Sheets and the Reconstruction of Anthropogenic Changes in Greenhouse Gas Concentrations

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Objectives: The central objective of our work is to improve our knowledge of the history of anthropogenic changes in atmospheric greenhouse gas concentrations, and our understanding of the geochemical processes which have influenced the observed concentration history. We are focusing on the key greenhouse gases CO₂, CH₄, and N₂O, and on tracers of the processes influencing their anthropogenic transients, including $\delta^{13}\text{C}$ of CO₂ and CH₄, $\delta^{15}\text{N}$ of N₂O, and the O₂/N₂ ratio. The analytical work on our firn air samples is being extended to include freons, halons, SF₆ and methyl halides (here termed, "anthropogenically influenced trace gases").

Product: (1) An improved record of the increase in the atmospheric concentration and isotopic composition of CO₂, CH₄, and N₂O in the atmosphere, along with a better understanding of the biogeochemical processes governing this evolution. (2) Information about the atmospheric history of anthropogenically influenced trace gases during the last century. (3) An improved understanding of the way in which gases are trapped in polar ice sheets and, in turn, a more accurate chronology of the variations in concentrations of greenhouse gases over both anthropogenic and glacial/interglacial time scales.

Approach: Our approach involves measuring, at URI and collaborating institutions, the concentrations of greenhouse gases, their isotopic composition, and the O₂/N₂ ratio in air from the firn of polar ice sheets. (The firn is the upper, porous, layer of incompletely compacted snow making up the top 50-115 m of polar ice sheets.) We also measure the concentration and isotopic composition of O₂, N₂, and Ar; these

properties provide essential information about gas transport, gravitational fractionation and sample integrity. Collaborating laboratories also measure the concentrations of anthropogenically influenced trace gases.

Firn is porous. Therefore increases in greenhouse gas concentrations in the atmosphere lead to increases in the concentrations of these gases in firn air. However the impedance of the firn air is considerable, and air at the base of the firn typically has greenhouse gas concentrations which were present in the atmosphere anywhere from 10 - 50 or more years ago. Firn air concentrations of gases being added by man to the atmosphere depend on two factors. The first is the time dependent concentrations of these gases in air, and the second is the mixing rate of the atmospheric transients down into the firn. An understanding of mixing in the firn allows us to infer how the concentration and isotopic composition of greenhouse gases in air have varied with time from data on changes in the composition of firn air with depth at a site. Firn air studies thus allow us to extend the record of anthropogenic changes in atmospheric composition to times before these changes were measured by monitoring programs.

To some extent, firn air studies overlap with ice core studies. However, firn air studies allow us to collect large volumes of air with minimal alteration of the in situ composition. These samples allow us to analyze species which are difficult or impossible to measure in ice core samples, including the N₂O concentration, $\delta^{13}\text{C}$ of CH₄, the $\delta^{15}\text{N}$ of N₂O, the O₂/N₂ ratio, and trace gases which have low concentrations and must therefore be analyzed in large volume samples.

The relationship between atmospheric composition as a function of time and firn air composition as a function of depth is a complex one influenced by the following processes:

1) Advection: The surface wind stress causes advection of air through the top of the firn. Advection can extend to a depth of 12 m or more. This process causes the composition of air in the top layer of the firn to be similar to the composition in the overlying atmosphere.

2) Gravitational fractionation: Because firn is largely a diffusive medium, concentrations of individual gases increase with depth according to the barometric equation (Craig et al., 1988). The rate of increase is proportional to atomic or molecular mass. Gravitational fractionation thus causes CO_2 to be enriched relative to CH_4 , for example, and causes the relative heavy isotope abundance of all gases to increase with depth (Craig et al., 1988; Sowers et al., 1989; Schwander et al., 1993).

3) Atomic and molecular diffusion of gases: As a result of the anthropogenic transient, concentrations of anthropogenically added gases are highest in the atmosphere and decrease with depth in the firn. This concentration gradient drives a flux of greenhouse gases to depth, as noted above. Concentration - depth profiles depend on concentration - time profiles in air and diffusivity - depth profiles in the firn. Individual samples of firn air do not represent individual samples of the atmosphere, but instead represent mixtures of the atmosphere of different ages.

4) Differential diffusion: Gases diffuse at rates which decrease with increasing mass and radius. As a result, CH_4 , (for example) diffuses about 30% faster than CO_2 , and $^{12}\text{CO}_2$ diffuses about .4% faster than $^{13}\text{CO}_2$. If the CO_2 concentration of a firn air sample is that of the atmosphere 30 years ago, the methane concentration will be that approximately 22 years ago, and the $\delta^{13}\text{C}$ of the CO_2 will be less than the $\delta^{13}\text{CO}_2$ of air 30 years ago. Properly correcting for the effects of differential diffusion is absolutely critical for reconstructing isotopic values in air vs. time from firn air and ice core data.

5) Lock in: At the bottom of the firn, the tortuosity of the ice may be so great that gases will essentially not diffuse even though there is actually open porosity. The gas signal thus gets

"locked in" above the firn - ice transition.

To date most information about anthropogenic changes in atmospheric composition has come from studies of the composition of air trapped in bubbles of polar glaciers. Bubbles are trapped at the base of the firn as the metamorphism of ice finally eliminates all open porosity and causes about 10% of the volume of ice to be trapped air. The source of the gas in the bubbles is the air at the bottom of the firn. Thus the processes that convolute the composition of firn air also influence the composition of air in bubbles. This observation leads to our second objective: improving our ability to reconstruct anthropogenic and glacial/interglacial changes in atmospheric composition from ice core studies. Reconstructions from ice core studies will be much more accurate if they are based on a detailed understanding of firn air transport processes. Our ongoing studies of firn air composition are intended to contribute to this understanding.

Results to Date: By far the most interesting results come from our recent effort at South Pole. $\delta^{15}\text{N}$ of N_2 , $\delta(\text{O}_2\text{N}_2)$ (with respect to an arbitrary standard), CO_2 concentrations and CH_4 concentrations in the firn air are plotted vs. depth in Fig. 1. From 31-114 m depth, $\delta^{15}\text{N}$ increases with depth due to gravitational fractionation at a rate indistinguishable from that predicted by the barometric equation (Craig et al., 1988; Sowers et al., 1989). From 115 m depth to the base of the profile, $\delta^{15}\text{N}$ levels off and decreases slightly. This feature of the $\delta^{15}\text{N}$ profile reflects "lock in" of the composition. That is to say, channels are sealed in discrete horizontal layers of ice below 114 m, but other layers still have open porosity down to 122 m depth. The composition of the gas is thus "locked in" at 114 m depth, but large volumes of firn air can still be sampled out of horizontal layers retaining open porosity.

The anomalously high $\delta^{15}\text{N}$ value at 10 m depth reflects thermal fractionation (J. Severinghaus, personal communication). Seasonal temperature variations at the surface produce thermal gradients within the firn. Heavy isotopes become enriched in the colder regions (the firn in summer, the surface in winter). By 30 m depth, seasonal variations are damped out.

The small $\delta^{15}\text{N}$ decrease between 114-122 m depth may result from thermal fractionation due to polar warming. If South Pole has warmed

during the last century or so, thermal fractionation would enhance the ^{15}N enrichment due to gravitational fractionation, because warmer surface temperatures require more time to propagate to the base of the firm. $\delta^{15}\text{N}$ of air at the base of the firm would increase with time towards the present, as observed. This tentative interpretation may also apply to central Greenland (GRIP and GISP 2 sites), where $\delta^{15}\text{N}$ again decreases in the lock in zone.

CO_2 and CH_4 concentrations fall slowly to the atmospheric value of about 15 years at 114 m depth. In the lock in zone, these gases behave as expected, decreasing in the six m of the core to their atmospheric concentrations near the end of the 19th century, as inferred from ice core data. The increase in gas age of about 14 years in each meter of depth equals the number of years of ice accumulation in each meter (the ice accumulation rate is $\sim 1/15 \text{ m yr}^{-1}$).

The finding that we can sample large volumes of firm air as old as 100 years raises the possibility that we can use these samples to reconstruct most or all of the atmospheric transients for a wide range of gases. Accordingly work is underway to measure concentrations of CO , H_2 , freons, halons, and halogenated methyl compounds. Work to date suggests that our samples are free of contamination for most of these compounds. Work is also underway to measure the isotopic composition of CO_2 , CH_4 and N_2O in the South Pole firm air samples. Rather than doing this work ourselves, we have developed collaborative efforts with several outstanding analytical laboratories.

The O_2/N_2 ratio of firm air is of special interest to us. Keeling and Shertz (1992) have shown that this ratio decreases with time as O_2 is consumed by the burning of fossil fuel. The actual rate of decrease may deviate from the (known) fossil consumption rate. A deviation would reflect O_2 production (CO_2 sequestration) or O_2 uptake (CO_2 release) by the land biosphere, assuming that the ocean has been in balance. Thus the O_2/N_2 - time curve allows one to estimate the net uptake rate of CO_2 (positive or negative) by the land biosphere. This estimate, in turn, together with the known rate of fossil CO_2 production and atmospheric increase, allows calculation of CO_2 uptake by the oceans. O_2/N_2 rises smoothly with depth between 30 and about 95 m, where CO_2 falls to a concentration of about 335 ppm v. The O_2/N_2 increase is nearly identical to that

observed in firm air at Vostok (Bender et al., 1994), and is undoubtedly due mainly to O_2 uptake by fossil fuel burning. Taken at face value, the magnitude of the O_2/N_2 increase in the top 95 m implies CO_2 release during the past 15 years (and O_2 uptake) of about 1.3 GT C/yr by the land biosphere at South Pole as at Vostok (Bender et al., 1994).

Below 100 m, O_2/N_2 rises dramatically to a level far higher than the preanthropogenic level could possibly have been. This feature has now been observed in firm air at GISP 2, GRIP (Schwarger et al., 1993), DE 08, Taylor Dome, and Vostok (Bender et al., 1994) as well as South Pole. We have also found that the O_2/N_2 increase is accompanied by an Ar/N_2 increase in deep firm air. We note that O_2/N_2 and Ar/N_2 are both lower than atmospheric in ice core trapped gases (Bender et al., 1995), and conclude that the deep firm air O_2 enrichment is due to preferential exclusion of this gas from ice as bubbles close. The mechanism is unclear but probably related to the smaller diameter of O_2 and Ar relative to N_2 (Craig et al., 1988). The release of O_2 (and Ar) into the firm by closing bubbles induces fluxes of these two gases which will diffuse up the firm and raise O_2 concentrations all the way to the surface. A correction can be made for the anomalous O_2 as follows. We can determine the O_2 flux from the total gas content of the ice, the ice accumulation rate, and the O_2 deficiency in the trapped gas. Using this flux and the diffusivity of the firm, we can then calculate the anomalous O_2 content of the firm air and correct for it. Work along these lines is underway. The correction will lead to an increase (i.e., less negative value) in the calculated rate of net O_2 production and carbon sequestration by the land biosphere.

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The Atmosphere-Biosphere Exchange of Nitric Acid and Ammonia to a Mixed Forest

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Objectives: The atmospheric nitrogen loading of an ecosystem is accomplished by the wet deposition of nitrate (NO_3^-) and ammonium (NH_4^+) ions in rain, fog, and snow as well as the dry deposition of N-containing particles and gases (e.g., gaseous nitric acid (HNO_3), and ammonia (NH_3)). Although it is relatively easy to quantify a wet deposition flux, determining the dry deposition inputs of N to aquatic and terrestrial ecosystems has proven to be considerably more difficult. The dry deposition of N to a vegetation surface is thought to be a function of the micrometeorological factors that influence atmospheric turbulence as well as the physiological and environmental factors regulating the opening/closing of leaf stomata.

Furthermore, chemical properties can predispose a gas molecule to more effectively adsorb onto a leaf surface and/or dissolve into a wet surface.

The objectives of this study are: (1) to develop and evaluate different methods of measuring the dry deposition of gaseous HNO_3 and NH_3 to a forest ecosystem; (2) to identify the processes regulating deposition to the forest; (3) to assess the relationship between dry deposition and regional transport scenarios

Products: (1) a detailed understanding of the measurements and conditions required to determine the atmospheric flux of HNO_3 and NH_3 to an ecosystem. (2) Evaluation of two

independent methods of measuring dry deposition. (3) Estimation of the importance of the major biological and physical properties regulating gaseous dry deposition. (4) Assessment of the large scale chemical and meteorological conditions which favor HNO_3 and NH_3 dry deposition.

Approach: The vertical fluxes of HNO_3 and NH_3 to a forest ecosystem will be determined by the flux-gradient profile and the resistance analogy approaches. The profile technique requires atmospheric concentrations, wind speeds, and air temperatures be determined at two or more levels above the deposition surface. The resistance analogy method can estimate dry deposition with concentrations and windspeeds from only one-level

Ambient levels of HNO_3 and NH_3 are being determined at three different heights using the Mist Chamber/Ion Chromatography (MC/IC) technique. Briefly, the mist chamber sampler concentrates water soluble gases from a large volume (1000 liters) of air into a small volume (10 ml) of ultra-pure water, while the ions in the stripping solution are subsequently analyzed by

ion chromatography. At the same sampling heights, wind speeds are monitored by three-cup anemometers while ambient air temperatures are determined by differential thermistors in fan aspirated shields.

For the flux-gradient approach the flux of HNO_3 can be described as the product of the eddy diffusivity of HNO_3 (K_{HNO_3}) and the vertical gradient in the atmospheric concentration of HNO_3 ($d\text{HNO}_3/dz$) above the surface. The challenge of the flux-gradient technique is to find a suitable method to approximate K_{HNO_3} . Traditionally, K_{HNO_3} has been assumed to be similar to the diffusivity of sensible heat (K_H) of momentum (K_m). Hence this method also requires the determination of the eddy fluxes of heat and momentum provided by other researches at this site.

The resistance analogy approach incorporates the three major physical processes involved in the uptake of a gaseous substance by a surface. These serial resistances to deposition can be described as the bulk aerodynamic resistance (R_a), the boundary layer resistance (R_b), and the surface uptake resistance (R_c).

The aerodynamic resistance is a measure of the stability of the atmospheric boundary layer between the receptor surface and the sampling height z and can essentially be described as the degree of turbulent mixing. A gas molecule that is turbulently mixed to a receptor surface must still diffuse through a thin viscous boundary layer very near the surface. This near-surface transport, which is mainly molecular diffusion, is incorporated into R_b . The surface resistance, (R_s), is a product of biological parameters (such as cuticular resistance) and the ability of the gas to adsorb to a leaf surface. The cuticular resistance is a bulk quantity that can be estimated by photosynthetically active radiation (PAR) and then scaled up to the canopy level by the leaf area index (LAI).

Results to Date: The flux-gradient and resistance analogy approaches have been applied to determine the HNO_3 dry deposition flux for spring, summer, and fall periods over the last two years. The development and refinement of these techniques continues with the addition of more sensitive temperature sensors (July 1995).

One recurring problem in applying the flux-gradient approach to this site has been the difficulty in measuring a significant difference in ambient concentrations of HNO_3 and NH_3 between our top two sampling levels. Unfortunately, these concentration gradients are commonly less than the 10% resolution of our MC/IC technique (Figure 1), especially in the springtime before leafout (Figure 2). This problem could be solved with the ability to sample at higher levels above the canopy. Other N-gas dry deposition studies have been from sampling platforms commonly twice the height of the canopy. However, with a full canopy it is possible to apply the flux-gradient technique 50%-70% of the time, depending on meteorological conditions (Figures 2 and 5). This ability to measure a concentration gradient due to the increased LAI in itself shows an important effect of the large surface area of the canopy in facilitating the deposition of HNO_3 .

In an effort to understand what processes regulate the deposition of the gases and identify other deposition surfaces in addition to the canopy, we have begun to investigate the below

canopy gradients of these N gases (Figure 4). Preliminary results indicate that this may be a significant deposition mechanism that, as opposed to the canopy deposition, occurs all year long.

In addition, larger scale meteorological events regulate the transport of airmasses from different source regions and indirectly influence the flux of N to this ecosystem. An example of this occurred in June 1995 (Figure 5) as clean from the northeast was replaced in the afternoon by pollution from the southeast (Figures 6). By the next morning, a third airmass, perhaps of mid-western origin, with similar HNO_3 mixing ratios was impacting the site. The mixing ratio and flux of HNO_3 increased (Figures 5 and 7) with the afternoon southerly change of the wind direction. Although the mixing ratios and concentration gradients remained relatively large over night, the HNO_3 deposition velocity (Figure 8) remained low and then rapidly increased in the early morning hours.

The similarity of the Harvard University NO_y (courtesy of Bill Munger) and our HNO_3 fluxes

(Figure 7) is a common occurrence and suggests that HNO_3 is the primary depositing species in NO_y . While this would indicate that the NO_y flux is a good proxy measure of HNO_3 , we are still working to improve the flux-gradient method for use at other less well instrumented sites as well as assess the importance of NH_3 deposition to this ecosystem.

Manuscripts in preparation:

Determination of HNO_3 deposition to a forest by flux-gradient and resistance analogy approaches, in preparation, 1995.

Importance of coarse and fine aerosol deposition to a forest; an intercomparison of sampling techniques, in preparation, 1995.

The atmosphere-biosphere exchange of NH_3 in mid-latitude forests, in preparation, 1995.

Student participation: Barry Lefer (3rd Year Ph. D Student, 100%); Sean Donohue (90% Summer 1995); Barry Moushegian (30% Summer 1994/95); Amanda Fifield (25% Summer 1994/95); Kristen Olson (25% Summer 1994/95)

Atmosphere-Biosphere Feedback Mechanisms in Forest Ecosystems

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Objectives: The overall objective of this research is to increase our understanding about how mid-latitude forest soils respond to changes in the climate and the chemistry of the environment, and what these responses imply for net ecosystem carbon storage. Models of the climate system predict that global mean temperature will increase from 1.5 to 4.5°C during the next century (Houghton et al. 1992). One result of global warming may be changes in rates of temperature-dependent soil processes such as decomposition (Swift et al. 1979), net N mineralization and nitrification (Focht and Verstaete 1977), and trace gas fluxes (Andreae and Schimel 1989). Changes in chemical climate include increases in rates of atmospheric nitrogen (N) deposition, especially for mid-latitude forest ecosystems of North America and

Europe (e.g., Levy and Moxim 1989; Penner et al. 1991). There is evidence that, as with warming, chronic N additions to forest ecosystems can alter soil processes such as decomposition, net N mineralization and nitrification (e.g., Tamm 1990, Nadelhoffer et al., 1995) and trace gas fluxes (e.g., Melillo et al. 1989).

Seven questions organize this research:

- How will soil warming affect soil CO_2 effluxes over the long term (4 to 6 years)?
- How will soil warming affect CH_4 and N_2O fluxes between the atmosphere and soil over the long term?
- What are the long-term effects soil warming on the rates of N mineralization, nitrification

and nitrate leaching below the rooting zone?

- What are the relative effects of soil warming on the two major CO₂-producing processes in soils: microbial respiration and root respiration?
- Do soil warming and chronic-N additions affect soil carbon quality differently?
- Do soil warming and chronic-N additions affect soil N dynamics differently?
- What are the consequences of warming and N deposition for net ecosystem C storage?

Products: The products of this continuation proposal in year two will be a set of five papers: #1 The effects of long-term soil warming on carbon and nitrogen dynamics in an eastern U.S. deciduous forest. #2 Contributions of root respiration and microbial respiration to total soil respiration in an eastern U.S. deciduous forest. #3 The effects of temperature and soil moisture on methane fluxes between forest soils and the atmosphere. #4 Climate change and net primary production in the forest ecosystems of the northeastern U.S.: a comparison of two biogeochemistry models, PnET and TEM. #5 Soil N dynamics in a deciduous forest in response to warming: a ¹⁵N tracer study.

Approach: In year two of our three-year program, we will continue to address the seven research questions using a combination of field studies at the Harvard Forest and modeling. The first 3 questions involve a continuation of measurements of C and N processes on the 18 plots set up in the original soil warming study. Question #4 involves the measurement of CO₂ emissions from the new trenched-plot study that includes a warming treatment. The process-level comparisons related to soil C quality (Question #5) and soil N dynamics (Question #6) will involve work on both the original soil warming plots and the existing plots subjected to chronic-N additions for the past 7 years. These plots (30m x 30m, located in a mixed-oak forest) have been fertilized with NH₄NO₃ (0, 50 or 150 kg N ha⁻¹ yr⁻¹) since 1988 (See Aber et al. 1993 for details.). The final question (#7) concerning the consequences of warming and N deposition for forest C storage involves the application of four existing models to the Harvard Forest and the northeastern United States.

Results to Date: Our extensive literature reviews (Peterjohn et al. 1994, Kicklighter et al. 1994) and field work at the Harvard Forest and in other sites along a broad temperate forest transect indicate, not surprisingly, that CO₂ emissions from forest soils are primarily a function of temperature. During the first year of the study, we observed that the daily average CO₂ flux from the soil increased exponentially with soil temperature (Figure 1). Linear regression could explain 92% of the variability between temperature and the natural logarithm of CO₂ flux. The exponential relationship between soil temperature and CO₂ flux is in good agreement with the Arrhenius equation. The Q₁₀ was 2.5 and the activation energy was 63 kJ/mol for these data. Our observed relationship between soil temperature and CO₂ flux is consistent with data from other forests around the world (Peterjohn et al. 1994).

The estimated annual CO₂ fluxes from the control, disturbance control and heated plots for the first three years of treatment are summarized in Table 1. The increases in CO₂ flux due to warming were between 30 and 40% in years 1 and 3, while in year 2 the increase just under 15%. The interannual differences could be related to year-to-year variations in ambient temperature, with year 2 being cold relative to years 1 and 3. Year 2 was also the driest of the 3 years, and this too could have contributed to the smaller response of CO₂ flux to warming in this year. We are now conducting more detailed analyses of our data to explore the interrelationships among annual variations in temperature, moisture and CO₂ efflux.

Nitrogen Mineralization: Net N mineralization rates have continued to increase in the surface soil-organic layer plus the upper to 10 cm layer of mineral soil over the 4 years of the soil warming study. Increases due to warming were about 160% in the fourth year in combined soil layers (Figure 2). Although net N mineralization rates have increased in heated plots, neither inorganic N, dissolved organic N nor microbial N pools differed between control and heated plots. This suggests that microbial activity, but not microbial biomass, has increased due to warming.

Table 1. Annual CO₂ evolution expressed as kg C/ha for each of three years (July 1991 - June 1992, July 1992 - June 1993, July 1993 - June 1994).

YEAR	CONTROL	DISTURBED CONTROL	HEATED
1991-1992	7,100	7,900	11,100
1992-1993	6,800	7,600	8,700
1993-1994	8,000	8,300	10,800

¹⁵N Isotope Studies: We have been conducting a ¹⁵N "pulse-chase" study on the effects of soil warming on soil and root N dynamics since September 1992. This study involved injecting ¹⁵N-ammonium and ¹⁵N-nitrate (separately) into split-plots (0.5 x 1.0 m each) located in 3 disturbed control and 3 heated plots and following the movements of the tracers through soil, dissolved inorganic, dissolved organic and microbial N pools for 14 months following tracer additions. Solid soil pools included bulk forest floor samples (Oe + Oa, or decomposed humus excluding fresh litter) as well as extractive (in non-polar solvent plus hot water), acid-soluble, and acid-insoluble organic matter. One half of all the bulk soil and fractionated forest floor samples we prepared were analyzed for ¹⁵N during 1995. (We cut back on the number of samples analyzed for ¹⁵N in order to meet budget cuts.) We are now analyzing the movements of the tracers through these pools in order to quantify the effects of experimental warming on the fates of ammonium and nitrate fluxes through soil organic matter pools and into plant roots. We anticipate that adequate information can be derived from our reduced number of analyzed samples to meet this goal, however, we need to complete our data analysis this winter in order to make a final assessment.

We have now completed analyses of the ¹⁵N tracers through soil microbial, soil solution and fine root pools. The short-term fates of the ¹⁵NH₄ tracers were consistent with independent *in situ* measures showing marked increases in net N mineralization in warmed plots. Our tracer study showed trends for increased gross N mineralization (total N flux from organic to mineral N pools) and for decreased NH₄ consumption (assimilation by soil organisms: roots and microbes) in heated versus disturbed control plots (Figure 3). Although neither of these processes alone were significantly different between treatments, net N mineralization (the difference between gross N mineralization and

NH₄ consumption) was almost 2 times greater on heated than on disturbed control plots. These results show that net fluxes of organic N into mineral N pools are an order of magnitude smaller than gross fluxes. Therefore, small (and generally undetectable) changes in gross fluxes due to warming can greatly alter N availability to plants.

Further analyses of our longer-term data on microbial N, dissolved organic N (DON), dissolved inorganic N (DIN), fine root N and soil organic matter N will provide more insight into the effects of warming on overall plant-soil N cycling. Recently summarized data on ¹⁵N natural abundances in samples from warmed and disturbed control plots (not on the ¹⁵N-tracer subplots) show that the overall effect of warming has been to make older, more resistant soil N fractions available to microbes and plants as evidenced by increases in (¹⁵N values of fine roots, microbes and dissolved N (DON+DIN) in heated vs. control soils by 1992 (Figure 4). The increased (¹⁵N values of these biologically active pools on the warmed plots suggest that much of the N in these pools was derived from older, more ¹⁵N enriched (See Nadelhoffer and Fry 1988) organic matter pools.

Modeling: We have begun to explore approaches to scaling our soil CO₂ efflux results from the site to the region. In one facet of this work, we considered issues associated with spatial and temporal aggregation in estimating regional CO₂ fluxes from temperate forest soils (Kicklighter et al. 1994). We developed an aggregation approach to estimate soil CO₂ efflux for the globe's temperate forest region. The flux data from the small static chambers are linked with regional databases on vegetation type and climate parameters at a 0.5(x 0.5(resolution throughout the temperate zone. Estimated annual soil respiration in temperate forest soils is 12.9 Pg C under the current climate (Kicklighter et al. 1994).

We have also used the data from the soil warming studies to modify our whole-ecosystem model (TEM - Terrestrial Ecosystem Model) which we have used to evaluate the potential impacts of climate change at the regional (e.g., McGuire et al. 1992) and global scales (Melillo et al. 1993, 1995). Currently, we are comparing TEM to PnET (Aber and Federer et al. 1992). Preliminary results indicate that they yield similar estimates of regional NPP for contemporary climate (PnET = 145 Tg C/yr; TEM = 140 Tg C/yr).

Finally, We have compared the results of the MBL/SPA for net ecosystem exchange of carbon and latent energy with the measurements made at the EMS tower for 25 days in the summer of 1992. We show a strong correlation between predicted hourly CO₂ exchange rate ($r^2 = 0.76$) and LE ($r^2 = 0.80$) with independent whole-forest measurement made by the eddy correlation (Figure 5).

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Role of Baroclinic Wave Amplitude and Transport Variation in Climate Change

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Objectives: The goal of this work is to obtain a comprehensive theory for the synoptic and planetary scale transient waves which explains the observed amplitude distribution and the associated fluxes of heat and momentum produced by these waves and provides a basis for understanding and predicting the sensitivity of transient waves and their associated fluxes to changes in boundary and constitutive conditions.

It is well known from spectral analysis of the transient geopotential variance of the midlatitude atmosphere that a sharp peak in the wavenumber-period spectra occurs concentrated at large scales (zonal wave numbers $m < 6$) and low-frequencies (periods $T \pm 10$ days (Fraedrich and Bottger, 1978; Schafer, 1979; Hansen et al., 1989)). However, conventional baroclinic instability calculations (Gall et al., 1979), predict

a broad maximum of the variance at synoptic scale ($8 < m < 12$) with associated period of a few days. Moreover, observations of the zonal wavenumber 5 eastward propagating wave with a period of approximately 10 days (Salby, 1982; Schoeberl and Krueger, 1983; Randel and Stanford, 1985) reveal characteristic episodic amplitude fluctuations with durations of approximately 2 days and energetics analysis of these waves confirms active baroclinic conversions during these periods. We are developing a theory that accounts for the spectrum of variance and fluxes and allows calculation of the sensitivity of these quantities to perturbation of boundary and constitutive conditions. In addition, this theory is being extended to provide a means of identifying the underlying dynamics producing the observed variance. This is a first step towards the goal of observation based system identification which is a powerful method for evaluating and improving climate models.

Approach: Previous attempts to explain the observed variance and transport properties recognized that the observed variance at low frequencies and large scales resembled the response of the atmosphere at these large scales to stochastic forcing. In their study Egger and Schilling (1983) employed an equivalent barotropic model of the atmosphere with a constant zonal flow. To obtain the observed response at large scales they needed to assume the forcing spectrum to be spatially red. However, the behavior of this dynamical system is determined by the fact that it is governed by a normal dynamical operator. In such a normal system the magnitude of the response of each normal mode is inversely proportional to its rate of dissipation, and the dominant spectral component is the least damped mode, when weighting by the spectral power of the forcing at each modal frequency is allowed for. These normal dynamics lack the essential processes of baroclinic/barotropic growth mediated by exchange of energy between the mean flow and the wave field. A theory of stochastic dynamics as it applies to the atmosphere that does take into account the pivotal non-normality of the underlying dynamics has been developed under NIGEC support (Farrell and Ioannou, 1993, 1994, 1995). The maintained variance in this non-normal system is not determined by a balance between the energy input by stochastic forcing and the energy lost to dissipation, as is the case in familiar normal systems, but rather the primary

balance is between dissipation and energy transferred from the mean flow by the perturbations with the energy input by the stochastic forcing playing a relatively minor role. This source of energy from the mean to the perturbation field leads to greatly increased variance compared to what would have been anticipated from the modal dissipation alone. It was found using these methods that forcing at a level of 1 Wm^{-2} is capable of maintaining the observed transient energy of the midlatitude atmosphere and of producing the observed transient heat flux (Farrell and Ioannou, 1993, 1994, 1995).

At this time our work on the theory of variance and fluxes in midlatitude atmospheric jets is proceeding in three main directions:

1) Equivalent operator identification is being pursued in channel models and in a simplified AGCM. System identification involves using the relation,

$$C(\tau) = e^{A\tau} C(0)$$

to find the equivalent dynamical operator of the turbulent dynamics. In the above relation $C(\tau)$ is the statistically steady correlation matrix of the variables at lag τ and A is the dynamical operator. The procedure is to gather statistically stable estimates of $C(\tau)$ and $C(0)$ from long runs of turbulent channel flows and of the AGCM from which the underlying dynamical operator A can be obtained. This inversion process can be used to obtain the dynamical operator from observations for which the underlying dynamics is a priori unknown.

2) Storm track variability will be studied by solving the Lyapunov equation for a version of the NCAR CCM2 that includes zonal variation. This study will determine the sensitivity of storm track location to jet stream variability. The techniques being developed are particularly useful in discerning the mechanism underlying climate variation because the climate statistics are related directly by this theory to alteration in boundary conditions.

3) Equilibration studies are being performed on simplified channel models to test that the fluxes of heat and momentum produced by the stochastic parameterization that we have developed produce mean flow tendencies consistent with the overall mean flow forcing and

dissipation. This is a powerful check on the entire theory of stochastic turbulence parameterization and it also reveals the nature and sensitivity of the balance between forcing and flux divergence that is responsible for maintaining the observed jet structure. Preliminary results for the turbulent two layer channel model have been obtained and these show good agreement between the stochastic equilibrium and the observed statistical mean of the nonlinear simulation.

Results to Date: Consider the observed wintertime zonal mean baroclinic jet as shown in Fig. 1. The distribution of the maintained variance obtained using the non-normal stochastic theory is shown as a function of frequency in Fig. 2. This plot demonstrates that the pronounced response found near wavenumber 5 with an approximate 10 day period is consistent with stochastically forced baroclinic dynamics. Comparison with observations (Fig. 3) reveals that the derived spectra are in remarkable agreement with observations.

Publications:

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Integrating an Ecosystems Model into a Global Change Impact Assessment

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Objectives: To couple an ecosystems model into an integrated framework for assessment of global change. The Integrated Framework constructed by the MIT Joint Program on the Science and Policy of Global Change includes an economic model for analysis of greenhouse gas emissions and mitigation proposals, a model of the biogeochemistry of the climatically important species, and a global climate model. To achieve a fully integrated assessment, the Terrestrial Ecosystems Model (TEM), constructed by the Ecosystems Center of the Marine Biological Laboratory at Woods Hole, Mass., has been coupled with the other Framework components. In addition to the development of measures of environmental impact for use within the integrated assessment, the research is exploring the use of the Framework to provide key inputs to TEM (including experiments on the consequences of using a two-dimensional (2-D) climate model rather than a 3-D GCM), and the inclusion of feedbacks from ecosystems to climate.

Products: (1) Development of common data sets (elevation, cloudiness, precipitation, temperature, potential vegetation and soil texture) for use in the component models of the MIT Integrated Framework, including the TEM. (2) Coupling of the TEM with the MIT 2-D L-O (land-ocean resolving) climate model (Sokolov and Stone, 1995). (3) Comparison of estimates of changes in net primary production (NPP) and carbon storage, for doubled-CO₂ experiments, between the MIT 2-D L-O climate model and two 3-D GCM models. (4) Analysis of the relative role of temperature, precipitation and cloudiness in the aggregate effect of climate change on NPP and carbon storage. (5) Sensitivity analysis of NPP and carbon storage, for ranges of values of input parameters in economics and climate components of the MIT Integrated Framework.

Approach: TEM requires for its climatological inputs monthly mean surface air temperatures, precipitation, and total cloud cover on a 0.5° x 0.5° grid (Melillo, et al., 1993). These three parameters are automatically produced by the MIT 2-D L-O climate model, but not on a 0.5° x 0.5° grid. Rather, the climate model produces zonal mean values of precipitation and cloud

cover, and separate zonal mean temperatures for land and ocean at each latitude. Given the impracticality of using a 3-D climate model in an integrated assessment (because of the large computational requirements), a zonal mean model was picked because the climate changes predicted by 3-D GCMs show that the changes depend primarily on latitude and only secondarily on longitude. In addition, the main longitudinal variations involve land-ocean contrasts, which are simulated in the 2-D model, at least as far as surface temperatures are concerned, since the lower boundary at each latitude is divided into separate land and ocean fractions.

To couple the two models, we retain the climatological fields already used in the TEM for the current climate, and use the climate model to predict just the changes in temperature, precipitation, and cloud cover. Thus, for each 0.5° x 0.5° point in the TEM, the climate model's predicted change in land temperature at each latitude is added to the climatological temperatures at each TEM grid point at the same latitude; and the percentage change in precipitation and cloud cover at each latitude is added to the climatological precipitation and cloud cover at each TEM grid point at the same latitude. Since the climate model's resolution is 7.8° in latitude, its predicted changes are interpolated to the 0.5° grid used by the TEM.

To determine responses to climate change with elevated CO₂, we ran TEM under (1) contemporary climate with 315 ppmv CO₂, (2) climate change with 522 ppmv CO₂, and (3) climate conditions in selected future years (assumed static) resulting from transient simulations of the economic, chemistry, and climate models of the MIT Framework. The TEM simulations driven by contemporary climate with 315 ppmv CO₂ was the baseline or reference for this comparison study. For contemporary climate, long-term monthly average data on precipitation, temperature and cloudiness (Cramer and Leemans, unpublished) were used. For this dataset, global average annual temperature, annual precipitation and cloudiness are 12.8°C, 795 mm and 46%, respectively.

For comparison between the MIT 2-D L-O model

and the 3-D GCMs, we used climate outputs for 1xCO₂ and 2xCO₂ simulations from two 3-D GCMs: GISS (Hansen et al., 1983), and GFDL-q (Weatherald and Manabe, 1988). The spatial resolution (longitude x latitude) is 10.0° x 7.826° for GISS and 7.5° x 4.44° for GFDL-q. The climate outputs from GISS and GFDL-q were interpolated to 0.5° x 0.5° grid cells by applying a spheric interpolation routine to the data. For the MIT 2-D L-O climate, we applied the zonally averaged data to all the 0.5° x 0.5° grid cells within the latitudinal band. We generated "projected climate" by (1) adding the absolute difference in temperature between 2xCO₂ and 1xCO₂ simulations to the contemporary temperature data, (2) multiplying the ratio in precipitation between 2xCO₂ and 1xCO₂ simulations to the contemporary precipitation data, and (3) multiplying the ratio in cloudiness between 2xCO₂ and 1xCO₂ simulations to the contemporary cloudiness data, respectively.

Projected changes in global mean annual temperature, annual precipitation and annual cloudiness for the doubled -CO₂ scenario were +4.2°C, +11.0% and -3.4% for GISS; +4.0°C, +8.3% and -0.7% for GFDL-q; and +4.2°C, +11.5% and -2.6% for MIT L-O, respectively. All the GCMs predicted that temperature increase was low in low latitudes but high in high latitudes.

Results to Date: TEM estimated that global NPP increases substantially for climate change with 522 ppmv CO₂ but varies little between the three climate change scenarios (Fig. 1, upper panel). Along the 0.5° resolution latitudinal gradient, the response of cumulative NPP has a bimodal distribution with the largest increases in both tropical forest regions and the temperate ecosystems of the northern hemisphere. Elevated atmospheric CO₂ concentration would enhance water use efficiency of plants, while increased temperature and precipitation would result in higher decomposition rates of soil organic matter. As a result, more N would be released from soil to be available for plant uptake. Generally, the latitudinal distribution of NPP change under the MIT 2-D L-O climate scenario is similar to those under the 3-D GISS and GFDL-q climate scenarios, except for relatively large differences within the 50.5°N – 58.5°N and 66.5°N – 74°N bands. The change in annual cloudiness within the 50.5°N – 58.5°N band is projected over 20% higher by the MIT 2-D L-O model than by the 3-D GISS and GFDL-q models. High cloudiness would reduce photosynthetic active radiation, which in turn

would reduce gross primary productivity. Also, in the 66.5°N – 74°N bands, changes in mean annual cloudiness and mean annual temperature projected by the MIT 2-D L-O model were over 10% and 2°C higher than those projected by the GISS and GFDL-q models.

For climate change with 552 ppmv CO₂, TEM estimated that global vegetation carbon increases substantially (+17.3% for the MIT 2-D L-O, +18.3% for the GFDL-q, and 19.5% for GISS), while soil organic carbon decreases moderately, resulting in an increase in total carbon storage (Fig. 1, lower panel). The response of total carbon storage has a bimodal distribution with the largest increase in the northern temperate regions and tropical regions. The response of total carbon storage under the MIT 2-D L-O climate change scenario is similar to the response under the GISS and GFDL-q scenarios, except, again, for large differences within the 50.5°N – 58.5°N and 66.5°N – 74°N bands. Within these two latitudinal bands, the MIT 2-D L-O model projects relatively higher temperature and cloudiness than GISS and GFDL-q. Higher temperature most likely significantly increases the loss of soil organic carbon, while higher cloudiness results in a decrease of response of vegetation carbon due to lower annual NPP.

The simulation results showed that TEM-estimated NPP and total organic carbon storage responses for the MIT 2-D L-O and the 3-D GISS and GFDL-q GCMs climate change scenarios are quite similar to each other on global or biome scales. The differences in estimates of NPP and total carbon storage between the MIT 2-D L-O model and the 3-D GCMs climate change scenarios are much lower than the responses of NPP and total carbon storage to climate change and elevated atmospheric CO₂ concentration. The largest differences in estimate of NPP and total carbon storage between the climate change scenarios occur in high latitude in the northern hemisphere, where vegetation is dominated by tundra and boreal forest and woodland. Global warming is likely to result in a shrinkage of tundra and northward expansion of boreal ecosystems and temperate ecosystems (Cramer and Leemans, 1993). Further work is needed to improve climate change projection of the MIT 2-D L-O climate model for high latitude in the northern hemisphere.

In summary, use of the climate change scenarios

projected by the MIT 2-D L-O climate model for impact assessment and uncertainty analysis should provide useful information on the responses of terrestrial primary production and carbon storage on the global and biome scales.

Student Participation: Yuexin Liu (PhD, 33%), Oliver Schneider (BS ChE, 40%), Stephanie Shaw (BS ChE, 35%), S. Seago (BS Math, 5%)

Manuscripts and Presentations:

Response of primary production and total carbon storage to change in climate and atmospheric CO₂ concentration: A comparison between a 2-D climate model and 3-D GCMs, by X. Xiao, D.W. Kicklighter, J.M. Melillo, A.D. McGuire, P.H. Stone and A.P. Sokolov (in preparation).

Integrated Assessment: Case Analysis Using the MIT Framework, by H.D. Jacoby and R.G. Prinn, presented at the MIT Global Change Forum VIII, May 18, 1995.

Ecosystem Impacts: Accommodating Transients and Uncertainty, by J. Melillo, presented at the MIT Global Change Forum VIII, May 18, 1995.

Ecosystem Modeling and Integrated Assessment, by J. Melillo, presented at the Stanford Energy Modeling Forum Workshop on Climate Change Impact and Integrated Assessment, Snowmass, Colorado, August 16, 1995.

Linking Natural and Social Science Components of Climate Change, by H.D. Jacoby, presented at a NERC-NIGEC Seminar, Harvard, March 2, 1995.

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Figure 1. Latitudinal distribution of the projected change in annual net primary production and total carbon storage under the MIT 2-D L-O climate and 3-D GISS and GFDL-q climate with 522 ppmv CO₂ along the 0.5° resolution latitudinal bands.

Coupled Atmosphere-Ocean Climate Models

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Objectives: Current coupled atmosphere-ocean general circulation models have systematic errors in their simulations of heat and moisture transports in the atmosphere and ocean, and thus require large "flux adjustments" at the ocean-atmosphere interface in order to simulate the current climate (Gates et al., 1993). The objective of the proposed research is to ascertain the importance of various factors in determining the atmosphere-ocean interaction, and investigate how the simulation of these factors affect climate sensitivity. The results should give valuable guidance as to what is needed to improve the simulation of climate sensitivity in coupled atmosphere-ocean climate models, and how the model results are affected by "flux adjustments."

Approach: Our approach is to develop a series of coupled atmosphere-ocean models, each of which simulates some of the potentially important climate processes realistically, but is otherwise simplified so that it is efficient enough to carry out many experiments. These "process" models are then used to address the project's objectives.

Results-to-Date: In the project's first two years three simple models were developed and studied. The results are contained in the three project publications listed below, all of which have appeared during the past year. In addition some of the results from the Nakamura et al. (1994) paper were cited in a news report in *Science* (Kerr, 1994).

In the past year the Nakamura et al. (1994) model was used to study the interaction of the thermohaline circulation with global warming. It was assumed that CO_2 increases by 1% per year for t_0 years, and the evolution of the model's state was examined as a function of t_0 . The model's thermohaline circulation collapses if $t_0 \geq 30$ years because the poleward atmospheric eddy moisture transport increases and freshens the high latitude oceans. However, the processes primarily responsible for the increase in the atmosphere's moisture transport depend on whether the global warming is strong or weak. If $t_0 \geq 100$ years, the increase is due to the increase in the atmosphere's moisture content which, in the model, follows the Clausius-Clapeyron equation. In these cases, the thermohaline circulation collapses in about 200 years. In this limit the model's results are very similar to those obtained with the GFDL coupled atmosphere-ocean GCM (Manabe and Stouffer, 1994). If $30 \leq t_0 \leq 50$ years, only the initial increase in the moisture transport is caused by the Clausius-Clapeyron effect; subsequently, the increase is associated with the EMT feedback described by Nakamura et al. This feedback eventually leads to the collapse of the thermohaline circulation, but the collapse takes much longer, ranging from about 400 years when $t_0 \approx 50$ years to about 1400 years when $t_0 = 30$ years. In the GFDL model the thermohaline circulation did not collapse for these values of t_0 . However, our results show that whether the thermohaline circulation will in fact collapse for these moderate amounts of global warming in a given model is very sensitive to small errors in the model's simulations of any of the atmosphere-ocean interactions.

Most of the past year's effort was devoted to constructing more sophisticated coupled atmosphere-ocean models than those described above. These coupled models will use the Marotzke and Willebrand (1991) ocean GCM with a simplified global geometry (the MW model). In preparation for coupling with an atmospheric model, an extensive set of experiments was carried out with the MW model with different surface boundary conditions for the surface heat and moisture fluxes. The results showed that the ocean circulation was sensitive to zonal mixing in the atmosphere, but that if this mixing is assumed to be efficient within an ocean basin, then realistic conveyor belt circulations are indeed produced when the latitudinal variations of heat and moisture are based on observations. For example, the poleward heat transport in the Northern Hemisphere is 1.5 PW, and in the North Atlantic it is 0.9 PW. As in Marotzke and Willebrand (1991) the conveyor belt equilibrium is unstable to sufficiently large perturbations.

The experiments also showed that increased poleward moisture transport in the atmosphere leads to an increase in the North Atlantic thermohaline circulation, just the opposite of the response for a hemispheric model. In the global 3-D ocean the response is controlled by the hemispheric asymmetries. This calls into question the Manabe and Stouffer (1994) explanation for the collapse of the thermohaline circulation in the GFDL coupled GCM when global warming occurs. They cite the increase of the poleward moisture flux in the atmosphere as the cause, but in our model this has just the opposite effect. The factors controlling the strength of the thermohaline circulation in our model will be investigated further.

Work also proceeded on the construction of two atmospheric models that will be coupled to the MW ocean model. The first, simpler model closely parallels the Nakamura et al. (1994) atmospheric model. The atmosphere is assumed to have no seasonal cycle, to be symmetric about the equator, and to have no longitudinal variations. The surface wind stress is specified from observations, and the latitudinal variations of the meridional dynamical heat and moisture fluxes in the atmosphere are also specified from observations. However the radiative fluxes and the magnitude of the dynamical fluxes are parameterized as functions of the zonal mean sea surface temperatures. These parameterizations are the same as those used by Nakamura et al. (1994). The model was tested by running it with observed sea-surface temperatures. It then reproduces the observed atmospheric fluxes.

Work also proceeded on the construction of a much more sophisticated atmospheric model to couple to the MW ocean model. This model, which we call the SY model, is basically the 2-D zonal mean statistical-dynamical model of Stone and Yao (1990) developed at the Goddard Institute for Space Studies (GISS). During the past year two further modifications were made in the model and tested. The first was a reduction of the critical humidity for large scale condensation from 100% to 90%. This resulted in a much more realistic simulation of water vapor concentrations for the current climate. The second modification was the introduction of interactive cloud covers, using schemes that closely parallel those used in the GISS GCM (Hansen et al., 1983). This gives the SY model sensitivities and feedbacks similar to those of the GISS GCM (Hansen et al., 1984), e.g., the increase in global mean surface temperature when the atmospheric concentration of CO₂ is doubled is 3.9K in the SY model, and 4.2K in the GISS GCM.

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Student Participation:

Xiaoli Wang, MIT Ph.D. candidate, 100% of time; received \$7,800 from NIGEC funds.

Jeffery Scott, MIT Ph.D. candidate, 10% of time; received \$1,625 from NIGEC funds.

Project Publications:

1. Marotzke, J., and P.H. Stone, 1995: Atmospheric transports, the thermohaline circulation, and flux adjustments in a simple coupled model. *J. Phys. Ocean.*, 25, 1350-1364.
2. Nakamura, M., P.H. Stone, and J. Marotzke, 1994: Destabilization of the thermohaline circulation by atmospheric eddy transports. *J. Climate*, 7, 1870-1882.
3. Wang, X., P.H. Stone, and J. Marotzke, 1995: Poleward heat transport in a barotropic ocean model. *J. Phys. Ocean.*, 25, 256-265.

Report Not Received Due to Late Funding

Dr. Wallace Broecker, Columbia Univ., Analysis of Pb isotopic composition of grains from Heinrich layers

Progress Report Not Yet Received

Dr. Richard Wilson, Harvard, Reducing emissions of greenhouse gases by alternative energy sources

SouthCentral Regional Center

Robert G. Watts, Director

Introduction: The SouthCentral Region of NIGEC contains the states of Arkansas, Colorado, Kansas, Louisiana, Mississippi, New Mexico, Oklahoma and Texas. The office of NIGEC SouthCentral is located at Tulane University in New Orleans, Louisiana. The three primary objectives of the SouthCentral Region of NIGEC are to develop an interdisciplinary and multiple approach research program which addresses the research issues in the Department of Energy's Global Change Program, to attract more scientists with diverse expertise into the area of research in global climate change and its consequences, and to train and educate new scientists for the study of Global Environmental Change.

Organization and Administration of the SouthCentral Regional Office: The management team for the SouthCentral Regional center consists of the Director, Dr. Robert G. Watts, the Associate Director, Dr. Victor J. Law, and an Administrative Assistant Ms. Pat Smith. A Steering Committee, appointed by the Provost with the advice and consent of the Dean of Engineering and the Regional Director, will help to screen proposals from both Tulane and other regional institutions and will provide guidance as to which proposals best fit into the thrust areas of the Center.

Current Research Program: During the past year, the research focus areas of NIGEC SouthCentral have been 1) The prediction and detection of climate change with models and from paleo-data and 2) Modeling and measurements of sources and sinks of radiatively active atmospheric trace gases. The program is currently in a transition stage. In future years the paleo-data effort will be phased out and we will begin emphasizing impacts of climate change on crops and unmanaged or lightly managed ecosystems common to the SouthCentral region. Particular emphasis will be involved with research on the importance of regional hydrology in the linkage between climate change and its effects on these regional ecosystems. In addition, the research on trace gas sources and sinks will deemphasize methane. Instead, the emphasis will be on the net exchange of carbon in ecosystems within the region.

Sixteen projects were supported by NIGEC SouthCentral for the 1994-95 FY. Of these, six involved climate modeling (J. Cole of the University of Colorado, W. Cotton of Colorado State, J. Curry of the University of Colorado, S. Kreidenweis of Colorado State, G. North of Texas A&M, and R. Watts of Tulane University), four were paleo-climate studies (M. Hoffert of New York University, R. Dunbar of Rice University, M. Morantini of Tulane University, and L. Sloan of the University of California at Santa Cruz), three were concerned with trace gas sources and sinks (P. Bakwin of the University of Colorado, V. Gutschick of New Mexico State University, and V. Law of Tulane University), and three were studies of impacts or risk (H. Hodges of Mississippi State, D. Sailor of Tulane University, and C. Pendergraft of Tulane University). In addition, two projects involving impact assessments were funded as pilot studies from the Director's Fund (J. Ramirez of Colorado State and S. Bhattacharya of Tulane). Educational Efforts: Research projects funded by NIGEC SouthCentral during 1994-95 FY supported the education and training of Post-Doctoral Students, Graduate Students and Undergraduate Students. NIGEC scientists gave numerous public lectures on various aspects of global climate change. The SouthCentral Regional Director, Dr. Robert Watts has served for many years on the American Society of Mechanical Engineers National Committee on Environmental Heat Transfer and has been active in educating the general public and the engineering community on various aspects of climate change and impacts. He gave an invited talk at the 4th U.S./Japan Joint Seminar on Thermal Engineering for Global Environmental Protection in San Francisco in October, 1995 and an invited paper on climate variability at the ASME Winter Annual Meeting in November. He also organized and chaired a session at that meeting entitled "Energy in the 21st Century."

Requests for Proposals Process for FY 95 -96 Research Projects: In the early Fall of 1994 a Request for Proposals was mailed to universities and research facilities in the SouthCentral region. The Requests for Proposals were sent to the Vice Presidents for Research, Department Heads and Deans (or equivalent) for each of the universities in the region that were judged to have viable graduate programs in at least one area that could in some way be related to the areas of interest to DoE and NIGEC. A list of people who had in the last two years asked for information from the Carbon Dioxide Information Center in Oak Ridge, Tennessee was obtained from that office, and Requests for Proposals were sent to those on that list who we felt should receive them. In addition, Requests were sent to all investigators who had applied to NIGEC SouthCentral in the past and approximately seventy five researchers whom the Director personally knew were actively engaged in related research. 42 Letters of Intent were received from 16 different universities and research facilities in 9 states.

Once the letters were received there was a seven week span for the preparation and submission of research proposals. We received 32 proposals from 15 different universities and research facilities in 8 states. The Regional Technical Review process was conducted by an outside mail review. We feel that this provides the best possible review by allowing for both specialized reviews and by reducing any possible conflicts of interest.

The proposals were then grouped according to the strengths of the reviews and how well they fit into our research focus areas. Groups I (recommended for funding) and II (recommended if any Group I proposals are judged not relevant or fail NTAC review) were sent to NTAC for review and comment.

Future Changes in the SouthCentral Program: NIGEC has been requested by the DoE to concentrate a considerable part of its future efforts in the areas of Climate Impacts and Integrated Assessment. The SouthCentral Regional Center intends to respond to this by requesting proposals concerned with the possible impacts of climate change on the south central United States, particularly regarding hydrological and ecological impacts. Proposals concerning parameterizations of processes within GCMs and methane modeling, except as they apply directly to impacts and integrated assessments, will not be funded in the future to clear the way for our new thrust areas.

Predicting Large-Scale Patterns in Vegetated-Surface Conductance for CO₂ and Water Vapor: Exploiting Physiological and Ecological Regularities

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Objectives: The overarching goal is to improve models of vegetation conductances for CO₂ and water vapor, for use in large-scale models of climate (GCM's) and biospheric responses, including crop and wildland productivity. To be transferable among sites and plant species, vegetation conductance models must be composed from process-based models of light interception and microclimate distribution on leaves, leaf energy balance, and CO₂ assimilation coupled with stomatal conductance. However, vegetation on one site and between sites is diverse in species composition and in attendant physiology. Thus, we are testing the hypothesis that the stomatal conductances, g_s , of diverse plant species on three sites (semi-arid rangeland, temperate cropland, and temperate deciduous forest) follow a proposed universal form in response to CO₂ assimilation potential, humidity, and water stress. This form is built on the Ball-Berry equation (Ball *et al.*, 1987), generalized to include water stress. Even with a universal form, however, the numerical values of parameters differ among individual leaves, among plant species, and among sites, which hinders scaling up predictions to large regions. We are thus testing hypotheses that there are mathematically simple patterns of parameter values in such variations, enforced by ecological requirements for efficient single-plant resource use and for stable competitive use of resources among plants.

Products: The primary product is a set of process-based models of leaf, plant, and stand stomatal conductance in response to the driving variables of top-of-canopy incident radiation, windspeed, air temperature, air humidity, and soil water status as volumetric water content. The models will apply to our range of test species and sites and will be structured to be transferable to diverse plant species and sites. Coupled with the models will be scaling laws for parameter values in the models in response to long-term climate, particularly radiant fluxes and

temperatures. The models explicitly will address all climatic effects other than acclimation to elevated CO₂. They will be structured to accept parametrization from physiological models of CO₂ acclimation. The models will be developed with high computational efficiency for computing-limited environments such as GCM's.

Approach: The first hypothesis, of a universal behavior of stomatal conductance among species and sites, is tested with leaf-level gas exchange on multiple species at three test sites. On the Jornada Range in New Mexico, we have been measuring gas-exchange on four dominant or locally dominant C₃ shrub species (*Larrea tridentata*, *Prosopis glandulosa*, *Flourensia cernua*, and *Gutierrezia sarothrae*) and two warm-season C₄ grass species (*Bouteloua eriopoda* and *Sporobolus flexuosus*). On the Evapotranspiration Laboratory site at Kansas State University, we have measured soybean (*Glycine max*). At the Harvard Forest in Petersham, MA, we have studied red maple (*Acer rubrum*) and red oak (*Quercus rubra*). Exchange of CO₂ and water vapor is monitored with a novel steady-state open-mode gas-exchange system on plants *in situ* under a range of imposed leaf-surface humidities (h_s) and natural variations of other environmental drivers (light fluxes, temperature, etc., and, importantly, water stress). The primary test is fitting data to the Ball-Berry equation (Ball *et al.*, 1987) for stomatal conductance, $g_s = mA_h_s/C_s + b$, where A is the CO₂ assimilation rate, C_s is the surface CO₂ concentration, and b is the residual conductance at zero assimilation.

Scaling to higher levels of aggregation is done with data on plant and community structure, and is tested with retrospective data on evapotranspiration (ET) measured with Bowen-ratio systems (Jornada Range; W. A. Dugas *et al.*, subm. to J. Arid Environ.) and eddy-flux correlation systems (Harvard Forest; Wofsy *et al.*, in press). Additionally, we will test models

against retrospective data on the FIFE experiment on grassland. In a field campaign scheduled for September, 1995, ET predicted from leaf to plant will be tested against sapflow gauge measurements, and regional ET will be compared with ET inferred from energy balance in Landsat TM pixels (method of Kustas *et al.*, 1989, using ground-based determinations of net radiation and air temperature; satellite-measured surface brightness temperature will be corrected for atmospheric absorption and surface thermal emissivity variations). To support the campaign-data interpretation, we are determining leaf area index and geometry on multiple spatial scales, from branch to community. As part of this, we are calibrating photographic and satellite vegetation indices to leaf area index on these multiple spatial scales. We are also measuring soil thermal emissivity, while developing efficient protocols for real-time measurements of same.

Canopy and regional conductance is being modelled at several levels. We are developing models of radiation transport (photosynthetically active radiation, or PAR; near infrared, or NIR; and thermal infrared, or TIR) in canopies that are highly inhomogeneous spatially, such as shrublands. Computationally affordable models, using novel statistical descriptions of leaf display, will be tested against limited field data and also exact ray-tracing calculations developed by collaborator Y. Govaerts (Joint Research Centre, Ispra, Italy). Scaling to multi-species communities will be modelled with individual-based models and then composite models with effective community-average parameters of stomatal control. Finally, we are developing models of competitive plant water use and drought tolerance, to explain observable regularities in community-average conductances (cf. Schulze *et al.*, 1994).

Results to Date: A result that strongly encourages the use of universal process-based models of stomatal conductance is that well-watered plants of many species appear to follow the Ball-Berry law cited above (Fig. 1; many more data are still being compiled from field and laboratory campaigns). Even more encouraging is that all the species have close to the same value (10.0) of the slope parameter, m . A modest, positive deviation is shown by top leaves of relatively mature deciduous forest trees (Fig. 1c), which may be buffered from diurnal transpirationally-induced water stress by the high water capacitance.

A second major focus of this research is how water stress affects the conductance parameters. We find that (1) low soil water content (SWC) reduces both the Ball-Berry slope, m (Fig. 1d), and the leaf CO_2 assimilation capacity (maximal carboxylation capacity, in a separate submodel for assimilation A), and (2) the species diverge in the SWC threshold for these reductions and in the rate of reductions with decreasing SWC. It will also be important to elucidate how the different root or soil locations contribute to the signal (abscisic acid) sent from roots to leaves to downregulate stomatal conductance. The actual pattern will indicate how surface-weighted determinations, as by microwaves, must be interpreted to predict regional stomatal conductance under water-limited conditions, which predominate on an annual basis. To this end, we have also established a plot instrumented with time-domain reflectometry probes to resolve SWC at 15 locations near each of three *Larrea* shrubs. We will analyze g_s downregulation from maximal values in terms of weighted contributions from different soil volumes.

An important modifier of assimilation, and hence of conductance, may be photoinhibition of leaves (Baker and Bowyer, 1994) under high light with low temperature or drought-induced low stomatal conductance. In July, 1994 and June, 1995, we collaborated with M. Ball of the Australian National University to measure photoinhibition (PI) in the field, quantify its seasonal effects on assimilation and growth, and develop kinetic models of PI as dependent on excess electron transport rate as determined from light and temperature histories. The comprehensive field experiment planned for June, 1995 to May, 1996 has been delayed by excessive early-season seedling mortality, but methods for gas exchange, chlorophyll fluorescence measures of PI, and leaf microclimate have been tested in detail for the experiment one year later. The methods and models also apply directly to scaling up conductance in general, nonphotoinhibitory conditions.

For the tests of scaling conductance from leaf to branch, plant, community, and region, we have developed a transect on the Jornada Range, 1000 x 300 m. Fifty plants have been characterized for gas exchange, seasonal water balance, and soil variables (topography and soil moisture release curve). We have tested a number of methods of image analysis to

measure leaf area index on various spatial scales, either by end-member spectral mixing or vegetation-index (VI) calibration. We find that VI calibrated to local soil background and leaf optics is most reliable.

In addition to testing spatial scaling of conductance, this transect is being used to seek ecological regularities in conductance variations among plants. We have measured gas exchange on the fifty plants to determine variations in the Ball-Berry slope and the related leaf-internal CO_2 concentration (C_i) that is the major determinant in water-use efficiency and water-use rates. We are doing stratified ANOVA and regression analyses to assign degrees of control by local soil conditions and water access (root depth, inferred from plant size).

In the models of canopy and stand conductance, we have assembled standard models of light interception, microclimate, and conductance, in implementations that incorporate some computational advantages (Gutschick, 1988). Novel challenges arise in modelling of plant coexistence under competitive water use. One component of these models is solving for optimal physiological acclimation of individual plants. With tens of physiological parameters acting in highly nonlinear systems, both analytical mathematical and brute-force searches for optima are wholly infeasible. We have begun testing methods of simulated annealing to find the optima; the methods work for simplified versions of the physiology. A second component is explaining how stable patterns of genetically-based variation in conductance (and related m and C_i) can be maintained in the face of genetic recombination in progeny. To this end, we have developed models of alternating selection pressures. In simplified models, we find that coexistence limits are rather narrow. The implication is that community composition may be unstable under even modest climatic change.

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- Manuscripts in preparation and submitted:**
- Physiological control of evapotranspiration by shrubs: scaling measurements from leaf to stand with the aid of comprehensive models. Submitted to USDA for publication in special volume for Ninth Annual Wildland Shrub Symposium.
- Tests of universality of the Ball-Berry description of stomatal conductance in three biomes. In preparation for Plant, Cell and Environment.
- Presentations:**
- Models of water use and water-use efficiency in crops and native vegetation - limited flexibility in plant role in the hydrologic cycle?. Workshop on Use of Models in Environmental Decision Making, CSIRO and the Australian National University, 6 July 1994.
- Global-change research on plant water-use strategies. Ecosystem Dynamics seminar, The Australian National University, 7 July 1994.
- Physiological control of evapotranspiration by shrubs: scaling measurements from leaf to stand with the aid of comprehensive models. Ninth Annual Wildland Shrub Symposium, USDA. Las Cruces, NM, 24 May 1995.
- Student participation:** Kaustuve Bhattacharya 25%; Robert Core 25%; Erik Jackson 12%; Felicia Najera 25%; beginning 15 May, to 1 August: Jose Anchondo 50%; David Reta 50%; Cesar Rivera 50%; Pedro Sanchez 50%.

Figure 1. Stomatal conductance (g_s) as a function of the Ball-Berry index, in a variety of plant species at three research sites, as identified in legends.

Impact of Climate Change on Flower and Fruit Production in Cotton

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and

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Objectives: To determine the effect of high CO_2 and variable sinusoidal temperatures on the production of cotton reproducing structures, and to simulate cotton crops based on weather hypothesized in global climate change models.

The overall objective of this work is to develop relationships that will provide the basis for upgrading a cotton crop model to predict the effects of elevated CO_2 environments and the hypothesized global warming trends on cotton production. The results from this work provides

the basic technical information from which such relationships can be developed, and extrapolated to many seed-bearing plants.

Product: A cotton production model, developed in this laboratory, is commercially available. It is widely used for assisting cotton producers make in-season production decisions. It is useful as a decision-aid for several management practices to optimize the most efficient utilization of the environmental resources. It does not, however, have an appropriate database to extend its

predicted responses to global warming scenarios. This work will extend the model so that the effect of increased CO_2 and temperatures can be predicted on cotton production. These model changes will allow one to predict with more confidence the effects of a few, or many, extremely hot days on cotton production, and it will provide some guidance regarding alternative management strategies to avoid these extremes.

Approach: Experiments were conducted in which cotton plants were grown until they had reached flowering in the natural environments. These plants were grown in 66 cm deep pots and maintained in a well watered and fertilized condition at all times. At first flowering, the plants were moved into naturally-lit plant growth chambers that were temperature controlled and the daytime CO_2 was kept at either 350 or 700 $\mu\text{l l}^{-1}$ CO_2 . The sinusoidal daytime temperature in the various chambers averaged 02, 0, +2, +5, or

+7°C from the forty year daily average July temperatures for Stoneville, MS (27.6°C). These temperature regimes were maintained for 28 days. Daily counts of flowers produced and abscised were determined. Photosynthesis and transpiration data was collected at fifteen minute intervals throughout the experiment. The experiment was replicated in time.

In a separate study, plants were grown in the natural environment and one set of plants allowed to become water-stressed. Less water was provided than was transpired each day for several days. This induced progressively more severe wilting among those plants. Leaf temperatures and air-leaf temperature differences were determined with an infrared thermometer on leaves in varying degrees of hydration near solar noon each day for several days. The leaves then were quickly removed and leaf water potential measured with the Scholander type pressure chamber technique.

Fig. 1. Effect of long-term July mean temperatures on number of bolls produced and retained for plants grown in ambient CO_2 concentrations. A: Stoneville minus 2°C, B: Stoneville mean temperature (27.6°C), C: Stoneville plus 2°C, D: Stoneville plus 5°C, and E: Stoneville plus 7°C.

Results to Date: The number of bolls produced by cotton plants increased within days after treatment, and with increasing temperatures up to the average July temperature plus 2°C for plants grown in ambient CO₂ concentrations (Fig. 1). Temperatures higher than 2°C above the daily July average caused the plants to produce slightly fewer flowers and bolls. The number of bolls retained by plants was also strongly influenced by time of exposure and by temperatures higher than July average plus 2°C. At both of the high temperature treatments, July average plus 5 or plus 7°C, the number of bolls retained was drastically reduced (Fig. 1).

The percent bolls retained dropped slowly as days after first flower occurred when the plants were grown at 29.1°C or lower (Fig. 2). The percent bolls retained declined after first anthesis due to the progressively greater boll load on the plants. High concentrations of CO₂ should increase the photosynthetic capacity of the plants and the overall productivity. However, the percent bolls retained dropped to nearly zero on plants grown at 33.3°C or above. There was about 15% more bolls retained due to doubling the atmospheric CO₂ concentration on plants grown at 29.1°C; however, at 33.3°C essentially all the bolls abscised regardless of the CO₂ concentration. It is apparent that such high temperatures critically damage the reproduction process (Fig. 2).

The number of bolls produced and retained are expressed as functions of temperature and CO₂ concentrations (Fig. 3). The fruit production efficiency increased as temperatures increased to 29°C, then it declined rapidly as temperature increased above 29°C (Fig. 4). The amount of vegetative biomass did not change as temperature increased (data not shown). Since the rate of fruit retention dropped so dramatically at temperatures above 29°C, the fruit production efficiency also dropped at those high temperatures (Fig. 3 and 4).

There was a linear relationship between air temperature minus leaf temperature and leaf water potential (Fig. 5). This suggests that as the plants become dehydrated and stomata close, due to low leaf water potential, the leaf temperature becomes warmer than its surrounding environment. Such an association is not new, but relatively little quantitative information is available. Since the model predicts leaf water potential based on soil water potential, air temperature and wind run, one may

predict the effective leaf temperature using the relationship between leaf water potential and canopy and air temperature differentials. The

Fig. 2. Effect of temperature and carbon dioxide enrichment on bolls produced and retained at the two higher temperature treatments.

Fig. 3. Effect of high temperature and carbon dioxide enrichment on number of bolls produced and retained.

Fig. 4. Effect of high temperature and carbon dioxide enrichment on fruit production efficiency.

addition of a canopy temperature subroutine in the model, GOSSYM/COMAX, to drive growth and phenological events will improve the predictive capability of the model under a wide range of water deficit environments. This will also improve the predictive capability of the model as it predicts high temperature effects on fruit retention.

Manuscripts as part of the MSU-NIGEC work:

Hodges, H. F. and K. R. Reddy. 1995. Temperature effects on cotton growth and development. V Congresso Brasileiro de Fisiologia Vegetal, Lavras, Minas Gerais, Brazil, 16- 20 July 1995. p. 35-58.

Reddy, K. R., R. R. Robana, H. F. Hodges, X. J. Liu, and J. M. McKinion. 1995. Influence of atmospheric CO₂ and temperature on cotton growth and stomatal characteristics. Ann. Bot. (In Review)

Reddy, K. R., H. F. Hodges and J. M. McKinion. 1995. Modeling temperature effects on cotton internode and leaf growth. Crop Sci. (In Review)

Presentations as part of the MSU-NIGEC Work:

Hodges, H. F. and K. R. Reddy. 1995. Temperature effects on cotton growth and development. 5th Brazilian Congress of Plant Physiol. Conf. July 16-20. Lavras, Brazil.

Reddy, K. R., H. F. Hodges, and J. M. McKinion. 1995. Climate change and cotton growth. Beltwide Cotton Production Research Conf. Jan. 4-7. San Antonio, TX, National Cotton Council of America, Memphis, TN.

Reddy, K. R., H. F. Hodges, and J. M. McKinion. 1994. Assessing cotton crop response to rising atmospheric carbon dioxide. Am. Soc. Agron., 86th Ann. Mtg. Nov. 13-18. Seattle, WA.

Reddy, K. R., H. F. Hodges, and J. M. McKinion. 1995. Projected temperatures and cotton fruiting. Am. Soc. Agron., 87th Ann. Mtg. Oct.29 to Nov. 3, St. Louis, MO.

Robana, R. R., G. Y. Lu., X. J. Liu, and K. R. Reddy. 1995. Impact of atmospheric CO₂ and temperature on cotton leaf morphology. Beltwide

Cotton Production Research Conf. Jan. 4-7. San Antonio, TX, National Cotton Council of Am., Memphis, TN.

Wang, X., and F. D. Whisler. 1995. Development of a weather database software for crop management. Beltwide Cotton Production Research Conf. Jan. 4-7. San Antonio, TX, National Cotton Council of Am., Memphis, TN.

Wang, X. N. and F. D. Whisler. 1995. The characteristics of weather patterns and their regional distributions. 25th Annual Workshop on Crop Simulation. March 13-15. Mississippi State, MS.

Whisler, F. D. and X. Wang. 1995. Use of weather database software in a crop management model. Beltwide Cotton Production Research Conf. Jan. 4-7. San Antonio, TX, National Cotton Council of Am., Memphis, TN.

Fig. 5. Relationship between canopy and air temperature differential and leaf water potential for cotton.

Effects of Clouds Upon Tropospheric Levels of Radiatively-Important Species

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Objectives: Clouds play an important role in tropospheric chemical processes. Their significance arises from several mechanisms by which they influence concentrations, reactions, and transport of radiatively-important trace species, including aerosols. Examples of important aerosol/cloud interactions which modify the radiative effects of aerosols include the transport of aerosols and aerosol precursor gases to higher altitudes by convective motion; variations in boundary-layer particulate matter concentrations that occur via the effects of removal by clouds and precipitation; and heterogeneous chemical reactions occurring in or on haze and cloud droplets.

Cycling through nonprecipitating clouds appears to be an important mechanism for deposition of sulfate onto aerosols, increasing the mass of particles resuspended from evaporating droplets. Number concentrations of resuspended particles may be changed by droplet collision/collection processes which occurred in cloud. The number concentrations and size distributions of particles are important in determining direct radiative effects due to scattering of solar radiation, and changes in the number concentrations of cloud condensation nuclei may have important indirect climate effects, manifested by changes in cloud microphysics and reflectivity.

The primary objectives of this study are to develop a description of sulfate aerosol uptake and release by cloud droplets, suitable for incorporation into existing cloud models; to merge this model with the CSU Regional Atmospheric Modeling System (RAMS); and to use RAMS to perform simulations of aerosol processing in several types of clouds, beginning with two-dimensional hill cap and stratocumulus clouds. These model runs will be used to evaluate the extent of aerosol processing for a range of initial chemical and meteorological conditions, and also to determine the feasibility of incorporating a detailed aerosol model into three-dimensional cloud simulations.

Products: (1) An aerosol model designed for use with the explicit cloud microphysics version of RAMS. (2) Assessment of Eulerian model performance using Lagrangian trajectories from a RAMS simulation to drive the detailed aerosol/cloud microphysics model. (3) Assessment of the feasibility of using Lagrangian trajectory simulations for studies of cloud processing of aerosol.

Approach: The general approach in this research has been to develop stand-alone models that can be tested independently, then to build complexity by combining these models. We begin by developing an aerosol model that is merged with an existing cloud drop microphysics model, which can be driven by a thermodynamic history file. This model can thus be used in stand-alone (Lagrangian) parcel mode.

Our aerosol/cloud drop model is next incorporated into RAMS and run in two-dimensional, Eulerian model mode. We next compare model results from this full RAMS run with those from a stand-alone parcel run, where the parcel has been driven by thermodynamics diagnosed from the same RAMS run; ideally, both models should produce identical aerosol and cloud drop fields. By analyzing differences between these predictions, we quantify numerical effects, including those due to the choice of Eulerian grid resolution in RAMS.

Results to Date: An aerosol model has been developed (Richardson, 1995) which is compatible with the treatment of cloud drops in the explicit-microphysics version of RAMS (Stevens et al., 1994). Our new model represents removal of particles by their activation to cloud droplets, and transfers the particulate mass to a solute phase within a cloud droplet size category. Rate equations have been developed which transfer solute mass to larger drop sizes as droplets grow by condensation of water vapor and by droplet collision/coalescence processes. Upon evaporation of cloud water,

solute is returned to the aerosol spectrum according to the mean size of particle re-generated from evaporated droplets.

After testing of sensitivity and performance of several models with various resolutions, a two-moment aerosol scheme was selected, with fourteen dry aerosol size categories; the two moments carried for each size category i are number concentration (N_i) and mass concentration (M_i). Twenty-five size categories are used for cloud droplets, each also carrying two moments for the liquid water distribution (number concentration of cloud droplets, D_j , and mass of liquid water in that size category, W_j). The solute (dissolved aerosol) mass within each droplet size category is represented by an additional variable, S_j ; the number concentration of solute particles is equal to the number concentration of cloud droplets. Our new scheme thus adds 53 new variables to the existing drop microphysics module.

To test the newly developed aerosol/cloud drop model, we selected a two-dimensional hill cap cloud for simulation in RAMS. The cloud approximates a flow-through reactor in this geometry, simplifying subsequent interpretation of model results. We also turned off collision/collection and precipitation processes in the initial studies. In the absence of physical and chemical processing, the upstream and downstream aerosol size distributions should be identical. Parcel trajectories through the cloud were diagnosed from the same run. Thermodynamic fields (total water, potential temperature, and pressure) and aerosol and drop distributions were saved along these trajectories.

Next, these saved thermodynamic fields were used to drive our aerosol/cloud drop model in its stand-alone, parcel model mode. Aerosol and cloud drop distribution histories from the RAMS and the parcel model runs were compared to quantify the effects of grid resolution in the Eulerian model. We found that the peak supersaturation occurs at different times in the two treatments, resulting in different number concentrations of aerosol activated and different droplet growth. In particular, more particles are activated in the Lagrangian model, producing smaller mean droplet sizes and narrower droplet size distributions. These results suggest that the RAMS framework may bias predictions toward broader drop distributions and lower droplet number concentrations. These effects may be

important in subsequent radiative transfer calculations.

As an additional test, a RAMS simulation using only bulk microphysics was performed, and thermodynamic fields along trajectories were again diagnosed and used to drive the parcel model. The resulting aerosol and drop distribution histories were nearly identical to those computed using thermodynamic fields diagnosed from the RAMS simulation including explicit aerosol and drop microphysics. However, the bulk-microphysics version of RAMS was completed in 10 CPU minutes, whereas the full version took over 10 hours. This comparison is very encouraging, as it suggests that the cloud thermodynamics may be simulated using bulk microphysics, followed by simulation of the details of the aerosol and cloud microphysical evolution using our parcel model. This scheme would not be suitable, however, for cases in which details of the cloud microphysics substantially influence the cloud history and thermodynamics. Marine stratocumulus clouds probably fall into this latter category.

Manuscripts in preparation:

Cloud Processing of Aerosol Using a Hybrid LES/Parcel Mode with Solute Following Microphysics. W. A. Richardson, Master's Thesis, Colorado State University, July 1995; also Dept. of Atmos. Sci. Technical Report.

Presentations:

A modeling study of the interaction between aerosol and marine stratus. Kreidenweis and Richardson, presented at the Fourth International Aerosol Conference, August 1994.

Simulation of aerosol cloud processing using a hybrid LES/parcel model with solute tracking microphysics. Richardson, Kreidenweis, Feingold, Stevens, and Cotton, presented at the American Geophysical Union 1995 Spring Meeting, May 1995.

Aerosol processing in a two-dimensional hill top cloud using solute following microphysics: Eulerian and Lagrangian model types. Richardson, Kreidenweis, Stevens, Cotton, and Feingold, to be presented at the XXI IUGG General Assembly, July 1995.

Aerosol processing in a two-dimensional hill top

cloud using solute following microphysics: Eulerian and Lagrangian model types. Richardson, Kreidenweis, Stevens, Cotton, and Feingold, to be presented at the Fourteenth Annual Meeting of the American Association for Aerosol Research, October 1995.

Contribution of morphology dependent resonances to the actinic flux inside cloud droplets. Fuller and Kreidenweis, presented at the Fourth International Aerosol Conference, August 1994.

Application of a trimodal monodisperse aerosol dynamics model: Results from a transport, transformation and deposition mode. Harrington, Kreidenweis, Walton and Penner, to be presented at the XXI IUGG General Assembly, July 1995.

Student participation: Wendy Richardson 50%; Yiping Zhang 5%.

Estimation of Global Methane Emissions from Rice Agriculture

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Objectives: The major objective of the current project is to describe via modeling the biokinetics and mass transport of methane produced from rice growing soils around the world. Mathematical models that utilize the resulting kinetic and mass transport sub-models can then be used to predict global emissions of methane from rice agriculture. Specific objectives are as follows:

- Replace, if necessary, the simple mass transfer coefficient aspects of the models with more precise components using multicomponent diffusion in porous media, such as the rice plant arrenchima. The work of A. Oyefodun investigates several candidate models for this process.
- Design optimal experiments to determine the kinetics of methane production from rice soils. The work of P. Kesavan addresses these issues.
- Investigate the possibility of introducing mutant enzymes into rice soils that might suppress methane production in these anaerobic systems. R. Enmon has begun a pilot research project in this area.

Products: Mathematical models implemented on personal computers have been and are continuing to be developed for both methane

production and transport in rice agriculture. Also, experimental procedures have been and are continuing to be developed in order to optimally define the kinetics of methane production from rice soils.

Approach: Algorithms have been developed to provide robust solutions to nonlinear regression problems constrained by differential equation models (Law and Sharma, 1995). These algorithms have been used in the work of Kesavan and Law (1995a, 1995b) to design optimal experiments for the determination of Monod kinetic parameters from laboratory experiments. Straightforward experimental data are available from prior year efforts. New kinetics studies have been performed on pyrene degradation by *E. coli* expressing a mutant cytochrome P-450. This work is leading to the development of mutant enzymes to suppress methane production in rice soils. The work of Oyefodun deals with the multicomponent transport of methane and oxygen in the presence of nitrogen through capillary tubes of varying diameter (similar to rice cultivar arrenchima).

Results to Date: The algorithm development work is summarized in the paper by Law and Sharma (1995). The important result is that all derivatives (sensitivity coefficients) can be computed efficiently at the same time that the

kinetic model differential equations are being solved. This not only speeds the computations but gives much more accurate derivatives, which are critical when deciding how well the Monod parameters are determined.

Kesavan and Law (1995a, 1995b) have completed two papers that utilize the sensitivity coefficient algorithm. General conclusions are as follows:

1. Product (i.e., methane production) data offer no additional statistical information over that of just substrate degradation data.
2. Four of the six Monod parameters can be determined from substrate degradation data alone.
3. All six parameters can be determined if biomass data are available in addition to substrate degradation.
4. Multiple spiking of batch reactors with substrate with significantly different concentrations allows full parameter determination.
5. Combined steady state and unsteady state data on substrate degradation alone allows all six parameters to be determined.

Enmon (1995) has shown that quantified cell growth and protein expression per cell in his system with mutant cytochrome match current protein production theories. Actual degradation rates and their dependence on protein concentrations have not yet been quantified; nonetheless, degradation trends are seen, providing possible data for testing developed models

Oyefodun (1995) used the "Dusty Gas" model to quantify the flux of methane through capillary tubes whose diameters are comparable to rice plant stem arrenchima. His computations include both steady and unsteady state and his models consider both isobaric and variable pressure systems.

Students: The following students have worked on the project during the past year:

Richard M. Enmon, Jr. has completed his M.S. thesis and will receive the degree in August, 1995. Details concerning this thesis are included at the end of this report. Padmanaban Kesavan is a Ph.D. student who has prepared two papers this year in association with this project. Adesina Oyefodun is a Ph.D. student who is now writing his Ph.D. thesis.

Publications:

Kesavan, P., V. J. Law, and S. K. Bhattacharya, Computation of Monod Kinetic Parameters from Batch Data, submitted to Biotechnology Progress, July (1995).

Kesavan, P., V. J. Law, and S. K. Bhattacharya, Computation of Monod Kinetic Parameters from Multiple Spiking and Combined Chemostat-Batch Experiments, submitted to Biotechnology Progress, July (1995).

Law, V. J. and Y. Sharma, Computation of the Gradient and Sensitivity Coefficients in Sum of Squares Minimization Problems with Differential Equation Models, submitted to Computers in Chemical Engineering, January (1995).

Todd, J.C., S.K. Bhattacharya, V. J. Law and V. Uberoi, An Integrated Modeling of Stoichiometry and Biokinetics of Anaerobic Processes, Environmental Software, 9, 33 (1994).

Methane Emissions and Mitigation from Louisiana and Philippines Rice Agriculture

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Objectives: The main objectives of the proposed research are to test selected inorganic compounds, rice varieties and alterations in rice production practices in Louisiana as mitigation options in reducing methane emissions from flooded rice fields. Additional objectives include the measurement of methane production, methane oxidation and quantification of root porosity and radial oxygen loss of Louisiana rice cultivars. The proposed research will help answer the questions of how methane emissions can be reduced without affecting rice yield or quality.

Products: Methane reduction techniques and management practices will be developed that can be used by rice producing countries. The methane data generated will be available to computer modellers that will help predict worldwide methane emissions under varying rice production and mitigation scenarios and the methane effect on global climate change.

Approach: Methane emission rates from flooded Louisiana rice fields under local rice production practices will be measured and used as controls for the proposed methane mitigation actions. Selected oxidized inorganic compounds, local water management practices, fertilizer placement techniques, and local Louisiana rice varieties will be evaluated as potential methane mitigation options.

Field experiments will be conducted at the Rice Research Station, Crowley, Louisiana to evaluate the proposed methane reduction options. Gas collection chambers will be used and head space gas samples will be collected twice a week during the first and ratoon cropping seasons from treatment and control plots. At the end of each growing season, treatment and control plots will be harvested and biomass (straw and grain) dried and weights recorded. Comparing treatment methane emission rates to control methane emissions the methane reduction potential of each treatment will be quantified and evaluated.

Results to Date: Several objectives of the proposed methane research have been completed. A field experiment at the Rice Research Station was conducted to determine the effect local cultivars of rice had on methane evolution from flooded plots. Semi-dwarf (Bengal, Cypress, Lacassine) and tall (Maybelle, Mars, Tebonnet) varieties were drill-seeded into a Crowley soil loam and methane fluxes were measured twice a week over the first and ratoon cropping seasons. Semi-dwarf rice varieties evolved significantly less methane over both growing seasons compared to the tall cultivars. Over the main cropping season, semi-dwarfs emitted an average $185 \text{ kg CH}_4 \text{ ha}^{-1}$ to the atmosphere compared to $300 \text{ kg CH}_4 \text{ ha}^{-1}$ for the tall varieties. During the ratoon season, semi-dwarf and tall varieties evolved 540 and $830 \text{ kg CH}_4 \text{ ha}^{-1}$, respectively. Compared to the tall cultivars the semi-dwarfs evolved 36% less methane over both seasons.

In a controlled laboratory experiment methane production in flooded rice soils as influenced by nitrate was studied under closely controlled soil pH and oxidation-reduction potential (Eh) conditions. Methane production was affected by soil pH and nitrate. Added nitrate reduced the amount of methane produced at each pH level investigated. Nitrate addition reduced methane production by increasing soil redox potential. Using methyl fluoride, a methane oxidation inhibitor, it was found that the added nitrate was not used in methane oxidation by methanotrophic bacteria.

Methane sources and sinks in a Louisiana rice soil and how they relate to atmospheric emissions were quantified. Total methane emission from the plant-soil system was compared with methane emission from surface soil between drill rows of rice (*Oryza sativa* L.). Results showed that over 95% of methane emitted to the atmosphere was through the rice plant. Average emission through the plant-soil system was $300 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ and $826 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ for the first and ratoon crops, respectively. By comparison average methane

emission from soil between drill rows was $2.1 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ for the first crop and $12.7 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ for the ratoon crop. Significant methane oxidation was measured in the surface oxidized layer in the soil profile between drill rows. Treatment with methyl fluoride inhibitor showed that methane emission from the soil would be five to ten time greater if oxidation did not occur in the surface layer. Laboratory studies of methane oxidation (also using methyl fluoride) showed that approximately 30% of the methane in the rice root rhizosphere was being oxidized by methanotrophs. Results showed that methane oxidation in the surface oxidized soil layer and in the root rhizosphere play an important role on limiting atmospheric methane emissions from Louisiana paddy soils.

Manuscripts and Current Status:

1. A colorimetric method for assaying dissolved oxygen loss from container grown rice roots. *Agronomy Journal* 86: 483-487, 1994. (H.K. Kludze, R.D. DeLaune and W.H. Patrick, Jr.).
2. Methane sources and sinks in paddy rice soils: relationship to emissions. *Agriculture, Ecosystems and Environment* 53: 243-251, 1995. (B.K. Banker, H.K. Kludze, D.P. Alford, R.D. DeLaune and C.W. Lindau).
3. Straw application effects on methane and oxygen exchange and growth in rice. *Soil Science Society of America Journal*, 1995. (H.K. Kludze and R.D. DeLaune). In Press.
4. Factors controlling carbon dioxide and methane production in acid sulfate soils. *Agriculture, Ecosystems and Environment*, 1995. (A. Jugsujinda, R.D. DeLaune, E. Sulaeman, C.W. Lindau and S.R. Pezeshki). In Press.
5. Effect of rice variety on methane emission from Louisiana rice. *Agriculture Ecosystems and Environment*, 1995. (C.W. Lindau, P.K. Bollich and R.D. DeLaune). In Press.
6. Influence of nitrate on methane production and oxidation in flooded soil. *Agriculture, Ecosystems and Environment*, 1995. (A. Jugsujinda, R.D. DeLaune and C.W. Lindau). In Press.

Presentations:

1. Methane emissions and mitigation options from Louisiana rice systems. Twenty-Fifth Rice Technical Working Group, New Orleans, Louisiana: March 5-9, 1994. (C.W. Lindau and P.K. Bollich).
2. Difference in plant response to soil redox intensity and redox capacity. American Society of Agronomy Annual Meetings, Cincinnati, Ohio: November 7-12, 1993. (H.K. Kludze, R.D. DeLaune and W.H. Patrick, Jr.).
3. Quantifying oxygen stress and root oxygen release in wetland plants. Third Symposium on Biogeochemistry of Wetlands, Orlando, Florida: June 26-29, 1994. (R.D. DeLaune, H. Kludze and S.R. Pezeshki).

Student Participation: Doug Alford 5%; Bradley Banker 5%.

Documenting Changes in Eastern Pacific Climate Using Corals: Base-Line Data for Validation of Climate Models

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Objectives: Isotopic and geochemical time-series generated from massive coral skeletons are now proving useful for reconstructing past variations in tropical surface oceanographic conditions before the time of instrumental records (i.e.: Shen et al., 1992; Cole et al., 1993; Quinn et al., 1993; Dunbar et al., 1994; Linsley et al., 1994). The usefulness of corals for paleo-environmental reconstruction is due to the continuous growth of most species, the deposition of annual time markers in the form of skeletal density bands, and the fact that many colonies live for centuries. This study is designed to develop long-term reconstructions of sea surface conditions using corals at two open ocean sites in the eastern Pacific; Clipperton Atoll and Cocos Island (Figure 1). The first phase of this project began in December 1994 and is focusing on the continued development of the skeletal oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotopic composition as a tracer of past oceanographic conditions. Composite $\delta^{18}\text{O}$ -time series are also being constructed where data from several cores are combined. Isotopic data from multiple cores at a single site allows assessment of the coherence of the discrete isotopic time-series. In particular, the composite records being developed from the suite of corals cores from Clipperton will provide one of the first tests of the continuity of interannual and long-term trends in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals between coral colonies in close proximity.

Products: (1) A multi-core, composite, annually averaged $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ reconstruction at Clipperton Atoll extending from 1994 to 1880. (2) The generation of sub-seasonal isotopic data on several Clipperton cores spanning the last ~10 years for calibration with satellite and in-situ temperature and rainfall estimates. (3) Sub-seasonal and annually averaged $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopic reconstructions from Chatham Bay and Pajara at Cocos Island extending back over 100 years. (4) The Clipperton and Cocos Island coral-based oceanographic reconstructions will add to the suite of multi-century coral records from the eastern Pacific. We have already published long records from the Galápagos Islands (Dunbar et al., 1994) and the Gulf of Chiriquí, Panamá

(Linsley et al., 1994). Once completed, this array of eastern Pacific sites will allow a regional comparison of interannual climatic variability and should provide valuable background information towards the development of climate change models and prediction.

Approach: Clipperton and Cocos Islands are both well placed to monitor regional-scale changes in the eastern Pacific. The sites are in off-shore settings and are impacted to varying degrees by the periodic occurrence of El Niño events and by the seasonal march of the Intertropical Convergence Zone (ITCZ). In the eastern Pacific, the El Niño Southern Oscillation (ENSO) is currently thought to be the main source of interannual climatic variability while seasonal movements of the ITCZ is the main expression of seasonal variability. The relatively stable SST field in the eastern Pacific warm pool drives convection in the eastern Pacific ITCZ. By reconstructing past changes in the eastern Pacific SST field, the frequency of ENSO events, and ITCZ precipitation, this study will attempt to document interannual and long term trends in eastern Pacific climate.

Our analytical approach is perform sub-seasonal and annually averaged sampling of coral skeleton for isotopic analysis. Coral cores are cut perpendicular to density bands with a high-speed band saw and slabbed into 7-mm-thick slabs. The slabs are cleaned with deionized water and X rayed (35 kV, 3 Ma, 60-90 s) with a Phillips Radiflour medical X ray unit using Kodak X-OMAT-G X ray film. X ray contact positive prints are used to develop a chronology based on annual density bands and as a guide for sampling along the axis of maximum growth. Subannual samples for isotopic analysis are collected by low-speed drilling with a Dremel tool and carbide tipped dental drill bit along the axis of maximum growth. In places where the sampling transect was changed along a coral slab, overlapping samples are collected in order to ensure that no interval is missed. Annually averaged samples are collected with a larger diameter drill bit. The entire growth year from the base of one high density band to the next is

Figure 1. Annually averaged sea surface temperature in the Pacific Ocean showing locations of Clipperton Atoll and Cocos Island. Note that Clipperton is situated in an region of stable, elevated SST's, referred to as the eastern Pacific warm tongue. Cocos Island is located inbetween Panamá and the Galápagos Islands, an area with a more pronounced SST gradient, just north of the equatorial cold tongue. This study is developing multi-century isotopic records of surface oceanographic conditions from both Clipperton and Cocos Islands.

removed and gently crushed in a mortar and pestle. For isotopic analysis samples are dissolved in 100% H_3PO_4 at 50°C: the resulting CO_2 gas is then analyzed with a VG Micromass 602E mass spectrometer upgraded with SIRA series electronics. Standards are analyzed 2 to 3 times daily. Generally, standard deviation of replicates and standards for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ is less than 0.1‰.

Fifteen coral cores were collected from massive heads of *Porites lobata* at Clipperton Atoll in April 1994. The colonies were all growing near the outer edge of a 10-13m terrace surrounding the atoll and have exceptionally high growth rates of 2.2 cm per year. We have measured $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the last ~10 years of coral skeleton in 2 cores at 2 mm resolution for calibration. To evaluate long term trends, annual average $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ has been analyzed in 3 cores. The longest of these extends back to 1880. The two Cocos Island cores were collected from dead colonies of *Porites lobata* in November 1990 from Pajara and Chatham Bay. The Chatham

Bay coral is approximately 200 years in length and the Pajara core extends back into the early 1700's.

Results to Date:

Clipperton Atoll (10° 18'N, 109° 13' W), lies within the eastern Pacific elongated warm water pool centered at 10°N and is situated at the boundary of the North Equatorial Countercurrent (NECC) and westward flowing eddy currents moving away from Central America. The seasonal SST range at Clipperton is ~2°C and SST averages 28.2°C. Clipperton is on the periphery of the influence of ENSO warm events, with SST anomalies averaging only +1°C. Satellite estimates of precipitation show pronounced seasonality with annual totals of greater than 3m.

For the Clipperton Atoll portion of this study annual and subannual samples are being analyzed. Sub-annual $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses are performed on selected cores and specimens at intervals of ~10 to ~20 samples per year. X-

rays revealed the presence of small (<0.5 mm) fish bite scars in many of the corals collected. Correlation of specific bites with the isotopic data showed that some bites effected the skeletal isotopic composition when sampled every millimeter. However, due to the extremely rapid skeletal extension rate, sampling at 2 mm intervals resulted in 10-12 samples per year and no noticeable effect of fish bites. Calibration of the isotopic data sampled every 2 mm was performed using in situ and satellite derived SST's, MSU estimated precipitation, monthly cloud cover and wind fields, and a salinity climatology. The annual $\sim 2^{\circ}\text{C}$ range in SST appears to be accurately recorded by the 0.44‰ $\delta^{18}\text{O}$ annual range found in these corals with only a small effect of salinity or $\delta^{18}\text{O}_{\text{seawater}}$.

The long term annually averaged $\delta^{18}\text{O}$ records from Clipperton all demonstrate that the small long term and interannual trends observed in the three cores analyzed are coherent (Figure 2). This preliminary data indicates that long term trends in the $\delta^{18}\text{O}$ composition of massive corals from different colonies at an oceanographically well mixed site are recording the same isotopic signal. Furthermore there is a close correspondence between the -0.4‰ $\delta^{18}\text{O}$ trend and a similar degree of warming in SST over the last 40 years. This suggests that the long term $\delta^{18}\text{O}$ trend is due to long term warming of the eastern Pacific warm pool, although the past variations in the $\delta^{18}\text{O}_{\text{seawater}}$ is a potential complicating factor in determining the exact degree of warming. A more rapid rate of warming occurs over the last ~ 10 -12 years in both the $\delta^{18}\text{O}$ and SST data. This coincides with a more frequent occurrence of ENSO warm phase events. It is not clear if the more frequent El Niño events are completely responsible for the more pronounced warming of the last decade. A long term increase in eastern Pacific warm tongue SST would have implications for precipitation and storm frequency in the eastern Pacific and in Central and western America.

The annually averaged $\delta^{13}\text{C}$ data reveal generally stable $\delta^{13}\text{C}$ values from the 1880's until the mid-1960's, when a $>1\text{‰}$ trend towards depleted values occurs that continues through April, 1994 (Figure 2). This pattern has not been observed in any of the other coral records in eastern Pacific. At this preliminary stage in the current study the origin of this $\delta^{13}\text{C}$ depleted trend is unclear.

Cocos Island ($5^{\circ} 30'\text{N}$, $86^{\circ} 30'\text{W}$) lies between the Galápagos Islands and Panamá and occupies a transitional oceanographic zone between the equatorial and coastal current systems. The island lies within the influence of the ITCZ, but is situated north of the equatorial cold tongue that effects the Galápagos Islands. Satellite rainfall estimates show that Cocos Island receives >3 m of rain per year in a pronounced wet season that lasts from April through November. Conditions become drier and slightly warmer during "warm" phases of ENSO when the ITCZ is shifted south. Oceanographically, Cocos Island lies near the terminus of the NECC and is thus influenced by waters of both western and eastern origin. Monthly maps of surface salinity in the eastern Pacific indicate that salinity is lowest during Feb-April, when the eastward flowing ECC is weakest. The map of average March surface salinity shows Cocos near the center of bull's eye of low salinity (about 31.3‰). In September salinity rises to 33‰ when the ECC is strongest, and a steep salinity gradient builds to the east as a result of wet season runoff and rainfall in Costa Rica, Panamá, and Columbia.

The two core we are analyzing are from Chatham Bay (North side) and Pajara (southwest side). Both cores were collected with dead, partially eroded tops and final chronology development awaits U-Th dating. The Chatham Bay coral was collected in $\sim 4\text{m}$ (12') of water in an isolated inlet near the mouth of a small river. Preliminary $\delta^{18}\text{O}$ data from the Chatham Bay core indicate that skeletal $\delta^{18}\text{O}$ in this coral has recorded both rainfall and SST variability. The proximity to a river outlet suggests that this site will be useful for tracking ITCZ rainfall and runoff. Skeletal $\delta^{18}\text{O}$ displays a larger annual range than observed at Clipperton, with most years showing two distinct $\delta^{18}\text{O}$ depleted peaks. Close examination of the Cocos Island MSU estimated precipitation record also reveals that many years contain two distinct rainfall maximums within the yearly wet season. The Chatham Bay isotope record shows a upward decrease in $\delta^{18}\text{O}$ of about 0.4‰ since the 1920's. Although the timing is not identical to the Clipperton results, this decrease in $\delta^{18}\text{O}$ is likely the result of both increased SST and ITCZ precipitaton. Future paired analyses of $\delta^{18}\text{O}$ and U/Ca should help separate the SST from $\delta^{18}\text{O}_{\text{seawater}}$ signal at this site.

The core from Pajara was collected in deeper water from the other side of the island from Chatham Bay. Comparison of the preliminary $\delta^{18}\text{O}$ data from this core to COADS SST show that this coral contains a larger SST component in the skeletal $\delta^{18}\text{O}$ composition. To date the upper half of the coral core from Pajara has been sampled at an interval of ~6 samples per year in an attempt to reduce the total number of analyses. Two intervals of indistinct banding also complicate the development of the correct chronology. The most striking feature of this isotope data is the large interannual range in both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. As the total length of this coral core is in excess of 300 years, potential correlations with interannual variability already observed in Panamá (Linsley et al., 1994) and in the Galápagos (Dunbar et al., 1994) make this an extremely important site.

The continuation of this project will expand the number of annually averaged time series, refine the chronologies and improve the calibration of the oxygen isotopic reconstructions. We plan to measure U/Ca in cores from both Clipperton and Cocos. U/Ca has been shown to be a potential proxy for SST. Through paired analysis of U/Ca and $\delta^{18}\text{O}$ we hope to determine the degree of SST variability versus $\delta^{18}\text{O}$ seawater variability.

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Manuscripts in preparation or in press:

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Presentations:

Linsley, B.K. and R.B. Dunbar, Sea surface temperature variability in the eastern Pacific warm pool since 1880; Stable isotopic evidence

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Other Products:

Reconstruction of surface oceanographic conditions at Cocos Island: Stable isotopic records from 2 multi-century coral cores, Mr. Robb Houston, M.S. thesis in preparation at Rice University.

Student participation:

Mr. Robb Houston, M.S. Candidate (80%); Dr. Braddock K. Linsley, Postdoctoral Research Associate (50%).

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Clipperton Atoll

Figure 2. (A) Annually averaged $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ from the three cores analyzed to date from Clipperton Atoll. All cores were collected near the outer edge of the terrace surrounding the atoll (Core C6A is from 11.3 m water depth, Core C4B is from 8.2 m water depth, and Core C2B is from 13.1 m water depth). The vertical line denotes the overall mean of the three data sets. (B) Composite annually averaged $\delta^{18}\text{O}$ data constructed by combining the data from three cores, and annually averaged SST data from COADS and NMC (Reynolds, 1988; and Reynolds and Marsico, 1993). The standard deviation of the $\delta^{18}\text{O}$ was calculated from the three overlapping cores back to 1938, from the two overlapping cores from 1938 to 1898, and using the single core from 1898 to 1880. Note the -0.4‰ $\delta^{18}\text{O}$ long term trend in conjunction with the $0.7\text{--}0.8^\circ\text{C}$ warming of SST.

Resources and Risk: Correlations for Risk Communication

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Objective: The objective is to develop a theory-driven typology of sets of attitudes relevant to environmental politics and policy. Survey and interview instruments and techniques that would produce theoretically, intuitively and statistically significant categorizations of the attitudes of individuals living in different geographic, economic, and social setting were developed. The second year's work will test the methodology in cases of alleged environmental injustice involving ethnic conflicts in Louisiana and Texas.

Product: The final product will be a short, easy-to-use survey instrument locating respondents on a cultural scale categorizing environmental attitudes along three ideological or perceptual dimensions. The instrument should help users explain and predict reactions to policy proposals. At this point, two instruments are under development. One is a relatively short (10 items) questionnaire in which respondents rank their levels of agreement or disagreement with statements relevant to environmental issues. The second is a longer (48 items) questionnaire designed as a follow-up instrument for those who complete the short questionnaire and are willing to be interviewed in depth. The longer instrument is aimed at exploring relationships between attitudes and policy options.

About 175 individuals responded to various versions of questionnaires, and about 40 were interviewed. A database of the responses of approximately 125 persons who responded to comparable items is being used to fine tune classifications and select the most useful survey items. At this point, cultural identification as determined by the short questionnaire is clearly a better predictor of attitudes than such standard demographic variables as age, gender, and education. The long questionnaire has proven to be a useful corrective for the short questionnaire, adding depth to the analysis.

Approach: Successful adaptation to climatic or other global environmental problems may require historically significant social, political and economic adjustments. Successful adaptation, that which imposes the least possible human and ecological cost, may depend on achieving levels

of cooperation that are as unprecedented as the threat itself. Of special interest, then, are social norms or preferences that influence attitudes about risk, cooperation, and the role of public policy. Given the variety of physical and social environments in which people live, and the complexity of individual experience, one expects attitudes to be diverse and complex. Constructing a typology that allows interpersonal and cross-culture comparisons is a difficult task.

The dominant methodologies through which we try to understand social behavior see people as individualistic, rational maximizers of their own self-interest, operating in a market-like milieu. Although altruistic, aesthetic, religious and collective motives are agreed to exist, the difficulty in measuring and predicting such fuzzy phenomena usually leads us to fall back on more mathematically amenable methodologies, often founded on the theory of rational choice. The study of perceptions of and reactions to risk is dominated by this individualistic methodology, because of the need to produce "objective" measures. It can be argued that individualistic methodologies take insufficient account of the ways in which social norms circumscribe and shape the beliefs and attitudes of their members. The success of the environmental movement in heightening the political and social salience of environmental issues may constitute an important change in social norms. However, a strong minority of respondents to this research seem not to have accepted the change.

The working hypothesis of this stage of the project is that people's attitudes about environmental policies are strongly influenced by their beliefs about whether natural resources are scarce or plentiful, fairly or unfairly distributed, and legitimately subject to public control. Two major assumptions are that people's attitudes about these things are patterned, rather than random, and that Grid-Group, or Cultural Theory (Thompson, Ellis and Wildavsky 1990; Douglas 1992) provides a useful basis for understanding and mapping these patterns. In terms of this theory, the concepts of "culture" and of "ideology" are very closely related. "Cultures" are at bottom systems of beliefs about the nature

of the world and of society. The social relationships within which people live their lives often shape and constrain their perceptions and opinions.

Respondents to the questionnaires and interviews were nearly equally divided between those who were randomly and those who were purposefully selected. Environmental activists, members of a conservative, evangelical church, environmental professionals (scientists, engineers, consultants), and people whose livelihood depends on the use of natural resources were purposely selected. Respondents ranked the levels of their agreement or disagreement with statements selected from the public discourse on environmental issues, and furnished common demographic information (age, education, gender, etc.).

Respondents were drawn from five geographic areas. These were El Paso County, (Colorado Springs), Colorado, Jefferson Parish (Suburban New Orleans), Louisiana, Washoe County (Reno), Nevada, and several Wyoming locations. The four counties are similar in population size and economic levels, but the Nevada county and the Louisiana Parish are far more dependent on natural resource extraction than are the Colorado or Alabama counties. The Wyoming respondents are members of families whose occupations are directly involved with natural resources — ranching, mining, oil production, and weed and pest control.

Results to Date: The notion that cultural theory is a useful guide to knowing what questions to ask and how to interpret the responses is supported by the results. Prior to the collection of any data, a coding system was set up, derived purely from theoretical considerations. To date, the coding system has not been modified, because not doing so provided a better test of the theory. However, it can be improved, now that there is a baseline for evaluating the results.

Responses were coded for each of three politically active cultural types: egalitarianism, individualism, and hierarchy. Cluster analyses were used to sort respondents into homogeneous groups. Based on the responses of 112 individuals to the short questionnaire, individualism and egalitarianism are strongly and negatively correlated ($-.67$, significance $.000$). Hierarchy correlates positively with individualism ($.28$, significance $.000$), and negatively with egalitarianism ($-.61$, significance $.000$). These correlations are Pearson's r , two-tailed.

The data support the conclusion that people who (1) are inclined to think that humans have a divine or natural mandate to dominate the earth; (2) are very strong supporters of the institution of private property; (3) very strongly prefer freedom to equality; (3) think that environmentalism is mostly a political bandwagon; (4) are unconvinced that rich countries have an obligation to financially help poor countries clean up pollution; (5) do not believe that population growth is the number one environmental hazard, (6) do not think a major change in our lifestyles is necessary to save the planet, and, (7) think our food supply is better and safer than ever before, are unlikely to support costly environmental protection and will probably resist government action that they believe will negatively effect them personally. These are the people theory labels "individualist." Those who are inclined to take opposite positions, egalitarians, are much more likely to support costly and intrusive policies. Hierarchs tend to agree with individualists, but are more open to compromise and to feel that both self-interest and *noblesse oblige* apply to helping poorer countries. Among those scoring in the top half of the respective cultures, the differences are often quite dramatic. Table 1 displays the attitudes of the various cultures with the statement that "*Rich and poor, we are all on this planet together, and rich countries must take financial responsibility for cleaning up global pollution; we are obligated to help the Third World.*"

Table 1: Attitudes toward the responsibility of rich nations to help poor clean up pollution

Culture	% agreeing	% neutral	% disagreeing
Hierarchy	26.7	22.2	51.1
Individualism	08.3	18.8	72.9
Egalitarianism	43.4	28.3	38.1

This research adds a valuable third-dimension to the analysis of survey responses. Finding, for example, that two-thirds of respondents report that they are highly concerned about the environment is by itself of limited usefulness to policy makers. In this study, 63% of all respondents rated their environmental concern as "high," 33% chose "medium," and only 4% said their concern was "low." However, cultural analysis helps us draw much more information from such data. It alerts us to the trap of lumping together people who, though they may be equally concerned about the environment, have considerably differing opinions about

policy. Though most respondents in all cultural categories report some concern about the environment, egalitarians claim considerably more than do hierarchs, and individualists seem less concerned than either of the other two. Table 2 displays cultural differences in environmental concern. This is a first step toward a more nuanced analysis of environmentally relevant opinions. It should be noted that the rankings of environmental concern were *not included* in the coding of responses that allocated respondents to particular cultural categories. These rankings, then, are independent of the cultural coding.

Table 2: Rankings of Environmental Concern by Culture

Culture	% "high"	% "medium"	% "low"
Egalitarian	95.5	4.5	0.00
Hierarchist	62.7	35.6	1.7
Individualist	34.6	53.8	11.5
Total	62.6	33.6	3.7

Cluster analyses indicate that individualists whose responses include more egalitarianism than hierarchy are significantly more likely to rank their concern "high" than those who are more hierarchic. Cluster membership is not significantly related to age, education, gender, or state of residence. However, it is related to such factors as activity in an environmental group. Environmental activists are significantly more egalitarian, as the theory predicts, than the average respondent, and the members of a conservative church in Colorado Springs were both more individualist and more hierarchic than the average respondent. In almost all ways, cultural characteristics are statistically better predictors of attitudes than the sorts of demographic data usually used as independent variables.

There are a number of ways in which cultures overlap. Very few in any culture want to leave the handling of environmental problems to experts. Though egalitarians are less than fervent about it, most support the institution of private property. The same is true when egalitarians are asked to choose whether freedom or equality is the more important. Very few choose equality, but they are less enthusiastic about choosing freedom than individualists are.

Western respondents, especially those in Colorado and Wyoming, were more individualist and less egalitarian than the Southerners. However, the most important caveat of this study is that, although the random sample and the non-random sample do not differ greatly overall, the results of this study to date cannot support extrapolation to the general population. The self-selective or purposely selective nature of the responses, the relatively small number of respondents, and the limited geographic and ethnic range of the respondents prohibit such extrapolation. It seems likely, however, that a representative range of attitudinal sets has been mapped.

Student Participation: None, though Tulane undergraduate and graduate students were used to test questionnaire items.

Publications: Two articles, one reporting the results of the study, and the other considering the sources of cultural differences, are in prep.

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Impact Assessment Schemes for Studies of Regional Climate Change

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Objectives: Water resource systems are designed and operated to cope with the natural variability of climate, such as with the occurrence of floods and droughts. Therefore, given the likely consequences of global change on hydrologic processes, a capability to assess its potential impacts on water resources must be developed. Given the high degree of uncertainty inherent in climate change predictions, one important aspect in carrying out this impact assessment is the development of improved general circulation models (GCM's) that account for the main interactions between surface hydrologic and biospheric processes, and global climate processes (see for example, Fitzjarrald et al., 1990; and Ramirez, 1991a). This requires increased understanding of land/atmosphere interactions, feedback mechanisms, and sensitivities so that improved land surface parameterizations can be developed. However, due to the large scale at which GCM's are integrated, large scale climatic information from the improved GCM's must be disaggregated to local and regional scales.

This proposal addresses the two different, but complementary research efforts introduced above. In order to increase our understanding of climate-hydrology linkages, this proposal a) examines the performance of hydrologic-biospheric models in current use within GCM's; b) proposes alternative or improved formulations of land surface models for use within GCM's; and c) develops climate inversion schemes for use in impact assessment studies at regional scales. Improvements in land surface models deal with several shortcomings of current parameterizations, such as a) current parameterizations do not take into account the subgrid scale spatial variability of geomorphoclimatic forcing; b) the effects of spatially variable interception and surface retention fluxes, as well as the dependence of these fluxes on precipitation intensity is ignored; and others.

Objectives

a) To develop techniques for aggregating/disaggregating local/large scale information hydroclimatic information to

large/local scale. These techniques should reproduce local features of regional climate as well as the overall relationship between regional and large scale spatial climate patterns.

b) To develop techniques for impact assessment studies of climate change on regional hydrology; and to apply it in order to define the potential effects of climate change on regional hydrology and water resources of the Rio Grande basin region in Colorado. Impacts on streamflow, and snow pack dynamics will be analyzed in conjunction with impacts on potential evapotranspiration, and precipitation. The analysis will include physically based parameterizations of hydrologic processes and, to the extent possible, it will include land surface/atmosphere feedbacks on an interactive basis.

c) To obtain improved land surface process parameterizations, that account for the main physical mechanisms affecting the hydrologic cycle at regional scales, including subgrid scale variability; and to evaluate the behavior of new and/or improved land surface models within a one dimensional climate model. The one dimensional climate model will be used to investigate the relative influence of land surface forcing and atmospheric environmental controls on climate and hydrologic processes.

Approach: Global climate change will manifest itself as variations in the seasonal and regional distributions of precipitation, surface runoff, evaporation, snowcover and snowmelt, soil moisture, vegetation cover, etc.; as well as changes in the frequency and magnitude of extreme events for a given region. A *statistical disaggregation* scheme will be developed as part of this project. Effects of climate change on regional hydrology of the Rio Grande basin will be assessed by disaggregating scenarios of changes in hydrometeorological fields at global scales (e.g., temperature and precipitation, etc.), to regional and basin scales, and using the disaggregated fields as inputs to a regional hydrologic model. Regional scale details of climatic change will be obtained by using a statistical climate inversion technique in which

the spatial covariance structure between the large scale and regional scale fields is preserved. The disaggregated fields will be used in order to force a detailed, physically-based, hydrologic model, namely the Precipitation Runoff Modeling System (PRMS) of the United States Geological Survey (USGS).

One dimensional climate models have been recently developed by several authors. Koster et al., (1988), Entekhabi and Eagleson (1989a). More recently, Ramirez (1991a, b) has developed a one dimensional climate model that is fundamentally based on the physical parameterizations of the CCM (see also Srivastava and Ramirez, 1993; Ramirez and Genovez, 1994). Although the basic model structure is similar to the two previous models, Ramirez' model has several additional options for land-surface processes, going from the simple bucket hydrology; to a more complex and explicit land surface parameterization based on a modified BATS scheme; to a statistical-dynamical, subgrid scale parameterization. The one dimensional climate model developed by Ramirez will be used for sensitivity analyses and as a screening model for the new and/or improved parameterizations. In addition, based on the BATS scheme of Dickinson et al. (1986), Ramirez (1991a) developed a capability to perform controlled simulations with an explicit land surface model that allows the specification of heterogeneity in both precipitation input, and soil and vegetation properties of the subgrid square.

Products: Methodologies will be developed in order to disaggregate global scale climatic fields to regional scales. This research effort will: a) develop statistical hydroclimatic disaggregation schemes; b) improve available parameterizations of surface processes in mesoscale and GCM models; c) improve our understanding of climate-hydrology linkages; and d) develop a general impact assessment scheme for studies of regional hydroclimatic impacts of global change. The statistical disaggregation technique should prove useful to water resource system managers and decision makers because it provides a) a capability to disaggregate global scale climate change predictions to local and regional scale that is readily usable; b) a capability to perform impact assessments of potential regional climate change on hydrology and water resources; and c) a capability to develop optimal management strategies which are based on sound,

scientifically-based policies.

Results to Date: A methodology for impact assessment studies, based on statistical disaggregation of large scale GCM information, has been implemented and successfully applied to the Rio Grande basin. Canadian Climate Center GCM output was disaggregated and used to drive the PRMS model for the Rio Grande Basin. Finally, initial improvements on several land surface parameterizations for climate models have been developed. Preliminary results of this work and of its application to specific regions of the world have been presented in India (Srivastava and Ramirez, 1993) and in an upcoming international conference in Chile (Ramirez and Genovez, 1994). Several presentations at meetings and refereed conferences have been made. A journal paper based on these results has been published (Epstein and Ramirez, 1994), and several are under preparation (see Appendix).

a) *Statistical Disaggregation Scheme.* All previous analyses of potential hydrologic impacts of global climate change (e.g. Lettenmaier and Gan, 1990; Nash and Gleick, 1991), have been performed by assuming that the predicted climate change scenarios at global scales can be linearly superposed on the regional scale climatological pattern. These procedures neglect important aspects of local scale climatic patterns that are the consequence of spatial heterogeneities in the local forcing. The statistical climate inversion technique developed, based on multivariate disaggregation methodologies, takes into account the spatial covariance structure of the given fields at both scales of aggregation. Disaggregation models produce regional fields of climate change scenarios that are internally consistent at the local, regional and global scales of aggregation, and that preserve the spatial covariance structure of the climatic fields at all levels of aggregation (see Epstein and Ramirez, 1994; Valencia and Schaake, 1973). This methodology has improved upon existing approaches because it accounts, in a probabilistic sense, for local climate forcing not well represented in GCM's, as well as for unknown causes of differences between GCM climatology and local climatology.

b) *Regional Hydrologic Impact Assessment.* The PRMS model has been implemented. PRMS is driven by solar radiation, temperature and precipitation, which can be obtained from GCM

simulations (Leavesley et al., 1983; 1987; and Leavesley and Stannard, 1990). Canadian Climate Centre GCM model output was first modified by the disaggregation scheme and then used as a forcing function for the watershed models. Geographic Information System (GIS) tools have been used in order to characterize basin geomorphology and define basin response in a way that is amenable for objective hydrologic analysis. GIS capabilities were also used in order to address scientific issues related to scaling of spatially heterogeneous land surface processes, and its effect on regional and global hydrologic cycles. In addition to hydrologic impact assessment, PRMS has been used in order to determine watershed response sensitivity to watershed model parameterizations under climate change conditions. Detailed results of aspects *a* and *b* above are presented in Epstein and Ramirez, (1994).

The results obtained from *a* and *b*, as summarized below, were excellent. The method developed greatly improves upon currently existing methods for climate disaggregation and, as shown (see Epstein and Ramirez, 1994), it allows for improved impact assessment studies under climate change scenarios. Several conference papers have been presented based on that work during the past year and a refereed journal article is currently in print.

c) Land Surface Parameterizations Two research efforts have been undertaken in this context. On the one hand a family of new land surface parameterization schemes has been developed that explicitly account for the effects of rainfall interception on the partition of water and energy at the surface. As a result of PILPS (Project for the Intercomparison of Land Surface Schemes) it has become clear that interception is one of two extremely important aspects of the land surface behavior in the partition of mass and energy at the surface. This new set of parameterizations accounts for subgrid scale variability of rainfall, for the dependence of interception on rainfall intensity, and for the dependence of interception on variable canopy cover. The family of parameterizations includes a deterministic and a stochastic parameterization.

On the other hand, the issue of regional scale estimation of actual evapotranspiration has been tackled by investigating and verifying the concept of the complementary relationship. Large scale

water budgets for the U.S. At spatial scales of 10 km have been performed and used to verify the complementary relationship and Bouchet's hypothesis for regional scale evapotranspiration. This hypothesis has been determined to produce extremely accurate estimates of actual evapotranspiration at regional scales for the region east of the Rocky Mountains (the study area).

The behavior of new and/or improved land surface parameterizations for climate models has been evaluated within the context of the one-dimensional climate model. Only within fully three dimensional model simulations can all of the feedbacks between the land surface and atmosphere be tested. However, these preliminary studies complement tasks above by evaluating the response to parameterization or aggregation of processes subgrid in scale within the one-dimensional climate model. The experiment strategy relies upon employing a hierarchy of surface soil, vegetation, topography conditions (e.g. no spatial variability, constant horizontal gradient, actual observed patterns) and varying complexity in parameterization. Emphasis has been placed on 1) defining the performance of current hydrological models used in GCM's; 2) establishing sensitivities to subgrid scale variability within the context of a fully coupled, interactive model (e.g.: sensitivities to soil texture, soil type, vegetation cover, land use, etc.); 3) establishing sensitivities to topographic effects on surface runoff; 4) establishing sensitivities of the different atmospheric parameterizations to the specification of complex land surface hydrology (e.g., effects of a moisture dependent surface soil albedo). Results up to date have examined and compared the behavior of seasonal distributions of hydroclimatic variables as a function of the land surface parameterization

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Epstein, D., and J. A. Ramirez, 1993: A Daily Spatial Disaggregation Approach and its Application in Hydrologic Sensitivity Analysis of the Upper Rio Grande to Climate Variability. *Invited American Geophysical Union Front Range Meeting*, Boulder, February 8 - 10.

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Energy-Use Implications of Climate Change

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Objectives: There are several important interactions between climatic change and the energy sector. The process of converting raw material resources into useful energy supply results in the release of large amounts of CO₂ which have the potential to significantly affect the global climate. In addition, climatic change plays a direct role in both the supply and demand for energy.

This study focuses on the impact of climatic change on the energy sector, and energy demand in particular. The first objective of the study is to identify the role of climate in affecting energy demand. The second objective is to develop a methodology for relating global climate change to regional scales, with an emphasis on predicting changes in regional energy demand.

Products: Short term products of this research include (a) statistical models relating climate parameters to energy demand, aggregated both by sector, and by end-use energy category (electricity/natural gas) and (b) new modeling approaches for relating results from GCM simulations to regional scales.

Approach: For the statistical analysis of energy demand and climate, historical energy-use data and climate data are gathered, and combined into a single data base. For various aspects of the analysis, this data base is disaggregated into sector data (residential, commercial, and industrial), seasons (winter and summer), and end-use (natural gas and electricity). The statistical approach involves developing simple linear models of energy use as a function of various climate parameters. These parameters are temperature, wind speed, humidity, and precipitation. Using temperature as a starting point, one-parameter models are developed. Additional parameters are then systematically added to the model to identify whether they constitute a statistically significant model factor.

The development of a modeling approach for casting global climate change into regional predictions requires output from both GCM simulations and regional climate models. Part of this problem has been addressed recently by

researchers using one of several approaches. The first step in our regional climate change study is to simply identify and evaluate existing methodologies. One approach for relating GCM output to regional scales involves nesting of a regional model within a GCM (Giorgi 1990). A limitation of this approach is that although different GCMs generally agree moderately well based upon global averages, they often yield predictions that are at odds on regional scales. One method of overcoming this limitation involves using local climatological data and expert judgment in the regional assessment of climate change (Robock et al. 1993). A third approach is based on the observation that different GCMs tend to exhibit similar regional responses when only results at higher altitudes are used. Karl et al. (1990) used this observation and statistical relationships developed by regression analysis of surface-based observations and free-atmosphere variables. While Karl used this approach to relate GCM simulations of current climate to measurements, we intend to extend the analysis to predictions of future climate change.

Results to Date: We have obtained climate data and electricity and natural gas data for the state of Louisiana for the period of the past ten years. The climate data were obtained from the Louisiana State Climatologist in Baton Rouge. The energy data were obtained from various publications of the Energy Information Administration (EIA). A preliminary statistical analysis has been conducted on these data. The results indicate that electricity consumption is very sensitive to temperature in the summer, but that natural gas consumption is more sensitive in the winter (Figure 1). The implication of global warming scenarios on the state of Louisiana seems to be an overall decrease in annual energy use. Because of the high cost of electricity relative to natural gas, however (roughly \$0.07 vs. \$0.03/kWh) the net economic impact on rate payers in Louisiana is expected to be a higher annual energy bill (Figure 2). This preliminary analysis includes only changes in temperature and assumes that other factors remain constant. Once the Texas (and California) data are available we will extend the

complexity of this analysis and attempt an intercomparison to identify regional climatic factors.

The above results for the statistical analysis are limited as they only represent the state of Louisiana. The analysis will soon be conducted for the state of Texas, and eventually California. The energy use data for Texas have already been obtained, and the climate data have been requested from the state climatologist.

The results for the regional climate change modeling aspect of this project are limited to simply having conducted a thorough literature search. We are just beginning to pursue an analysis similar to the approach of Karl. The necessary GCM output data have been identified. Specifically, we will obtain multi-year averaged, daily mean values of temperature, wind speed, pressure, and humidity for an entire year. In order to obtain the necessary data we have contacted the three major U.S. GCM modeling groups- NASA Goddard Space, the Geophysical Fluid Dynamics Lab, and the National Center for Atmospheric Research. The initial analysis, however, will only require data from one of these modeling groups.

Manuscripts in preparation/submitted:

Electricity Use Sensitivity to Climate and Climate Change, in press, World Resource Review.

Presentations:

Energy-Use Implications of Climate Change, presented at the 6th International Conference on Global Warming, San Francisco, CA, April, 1995.

Other products: Invited contribution to the Encyclopedia of Life Science Systems (EOLSS) in the area of energy systems and climate change (manuscript in preparation).

Student participation: Xiangshang Li, doctoral student (100% Jan. 95 to present, ~\$6,000); John Varriello, undergraduate student (50% during summer 95, ~\$1,500); and Greg Rumph, master's degree student (100% over summer 95, ~\$3,000).

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Robock, A., R. P. Turco, M. A. Harwell, T. P. Ackerman, R. Andressen, H.-S. Chang, and M. V. K. Sivakumar, 1993: Use of general circulation model output in the creation of climate change scenarios for impact analysis. *Climatic Change*, 23, 293-335.

Figure 1. Sensitivity of energy use to air temperatures for the state of Louisiana.

Figure 2. Consumer energy cost for the state of Louisiana, before and after hypothetical climate change.

Paleodata Calibration of Greenhouse Gas Forcing Effect on Climate

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Objectives: Global climate models (also known as general circulation models, or GCMs) predict future global changes due to anthropogenic production of carbon dioxide and other greenhouse gases that are outside the range of historical measurements. The only immediate and direct way to test model predictions of climate change against observations is to examine the ability of climate models to simulate large climate changes that have occurred in the distant past, due to greenhouse and other forcing. Through geologic evidence we know that the present climate is far from stable over the long term, and that there have been many intervals of geologic time during which the world was substantially warmer or colder than today. It is thought that radiative forcing from greenhouse gases was one of the primary forcing factors responsible for past global climate states, and so that element of climate change is examined in this project.

The overall objective of this study is to examine, via two methods, the ability of climate models to simulate large global climate changes that have occurred in the distant past. The more detailed working objectives are: 1) To define the planetary response to different levels of radiative forcing for different climate states in the past, using results of GCM simulations of these past intervals and separately using geologic data which represent the same information. These results will be used to evaluate the ability of climate models to predict the global forcing-to-response relationship. 2) To compare GCM simulations of these past climatic intervals with appropriate geologic data in order to evaluate the ability of the model to produce paleoclimate characteristics, including the correct pole-to-equator surface temperature gradient.

Products: (1) An estimate of the planetary response to various levels of radiative forcing for different climate states in the past will be made, using two independent methods. (2) An estimate of the climatic response to be expected from future increases in human-produced greenhouse gases, based on a geologic view of paleoclimate changes, will be produced. (3) An assessment of model performance under forcing conditions

different from those of today will be made; specifically, assessment of model estimates of global mean and zonal mean conditions, and an evaluation of the ability of climate models to obtain the correct forcing-to-response relationships under varying forcing conditions, will be delivered.

Approach: Using geologic data which represent several climatically extreme intervals of Earth's past, the planetary response to different levels of radiative forcing for different climate states in the past are being defined. This work is being carried out, in part, by utilizing the paleocalibration technique (e.g., Hoffert and Covey, 1992), in which the ratio of temperature response to forcing (defined as the climate sensitivity) is calculated separately for both model simulations and geologic evidence of paleoclimates. Results from GCM simulations of these intervals will also be compared with geologic paleoclimate data. The following specific questions define the research approach applied to this project:

1) Climate sensitivity (defined as the ratio of forcing to response): (a) Are the climate sensitivities of past climates inferred from geologic and biologic records the same for different climate regimes in Earth history? Time intervals of interest are the preindustrial present, the Last Glacial Maximum (~20,000 years ago), the middle Pliocene (~3 million years ago), the early Eocene (~55 million years ago), and the late Cretaceous (~75 million years ago). (b) Is the sensitivity deduced from the geologic data for the time intervals of interest different from that obtained by GCMs for the same time intervals?

2) Reconstructed paleoclimates: Compared to the geologic data, how well do GCMs simulate surface temperature (a) in the global average, (b) in contrast between high and low latitudes, and (c) in contrast between ocean and land regions, for the same past climate intervals considered in (1)?

3) GCM performance: The results of parts (1) and (2) may suggest directions for future model improvements. In order to improve GCMs an

increased understanding is needed of the dynamics of regional climate response, including feedbacks between the ocean, land and atmospheric systems.

Results to Date: Through the fraction of the year that the project has existed, the following results have been obtained:

1) Climate model experiments have been generated with the National Center for Atmospheric Research (NCAR) GENESIS climate model for (a) the preindustrial present (atmospheric pCO₂ set at 200 ppm), (b) the Last Glacial Maximum, (c) the middle Pliocene, and (d) the earliest Eocene.

2) Results of climate model experiments for the middle/late Cretaceous, generated with the same GCM, have been obtained from Dr. Eric J. Barron at Penn State University.

3) Geologic data which describe the surface climate conditions and radiative forcing conditions of the late Cretaceous Earth (an extreme warm period) and the Last Glacial Maximum (an ice age) have been analyzed and used to revisit and refine the climate sensitivity estimates made by Curt Covey (Lawrence Livermore National Laboratory) and Marty Hoffert (New York University) in Hoffert and Covey (1992). The revised estimates of climate sensitivity, along with the additional estimate of the early Eocene, are currently in review as a revised manuscript (see below).

4) Geologic data describing the climate and forcing conditions for the Earth during the extreme warmth of the early Eocene have been collected and analyzed. The Eocene data suggest a reduced climate sensitivity relative to the Cretaceous and Last Glacial Maximum data. Additional time intervals will have to be examined before any conclusions about climate sensitivity through Earth history can be made.

5) At the current point in this research, for the geologic intervals examined so far, the sensitivity estimates derived from the paleoclimate data are approximately consistent with the range of climate sensitivity predicted by the climate model. Estimates of climate sensitivity made from the geologic data reconstructions imply that the climate sensitivity of Earth through time lies in the lower half of model-predicted estimates of climate sensitivity that have been published.

6) A preliminary comparison of model-produced mean annual global surface temperature and of latitudinal surface temperature gradient to estimates of the same conditions derived from geologic data have been made for the Last Glacial Maximum, the middle Pliocene, and the early Eocene. The GCM produces global mean surface temperature estimates that are consistent with those derived from geologic data.

7) Comparison of model results to paleoclimate data interpretations indicates that the pole-to-equator surface temperature gradients produced by the GCM disagree with temperatures reconstructed from geologic paleoclimate data at both high and low latitudes for each time interval examined so far. Especially for warmer-than-present paleoclimates, the GCM appears to not completely match the latitudinal temperature gradient. The distribution of temperature change (for a past climate, relative to present climate) with latitude obtained by the model also fails to capture the changes recorded for both terrestrial and marine systems at many latitudes. The geologic paleoclimate records suggest temperature changes that are not uniform across latitudes, while the GCM appears more constrained to produce uniform temperature changes. Although preliminary, these results suggest that results from current GCMs may be suspect for some regional climate change predictions, for past, and by inference, future, climate changes.

Publications: A manuscript, *Paleoclimate Data Constrains on Climate Sensitivity: The Paleocalibration Method*, by C. Covey, L. C. Sloan, and M. Hoffert, has been submitted to *Climate Change* and the revised version is currently under review by the editor.

Supplemental Information; Remaining Work: The work that remains consists of: (1) data base creation for the middle Pliocene and the Last Glacial Maximum; (2) data base collection for the preindustrial present, a new addition to this project; (3) data collection to supplement the body of knowledge already collected for the Cretaceous, and to do the same for the early Eocene; (4) assessment of the reliability of the data in all cases; (5) final assessment of climate model sensitivity for these time periods, based on the sensitivities defined by the data collected in this project.

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Rapid Climate Change

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Objective: The transition between the most recent glacial maximum at 18 kya (thousands of years ago) and the current climate was punctuated with sporadic and abrupt shifts most prominently recorded in the region surrounding the North Atlantic Ocean. In order to understand how the climate will respond to climatic forcing associated with increasing concentrations of radiatively active gases, the type of behavior observed during this period needs to be understood. This period is an ideal candidate for study due to the amplitude of the climatic anomalies and the richness of data available.

Due to the regional nature of the observations, it is suspected that interactions between the ice sheet dynamics and variations in the thermohaline strength in the Atlantic Ocean are responsible for these events. Working under this premise, and designing a simple model that includes the major aspects of the climate system, we hope to reproduce the type of behavior observed during this period.

Product: The product of this research will be a model which includes the subsystems of the climate that are considered to be essential to reproduce the dominant features of the observed climatic readjustments. The system will be designed to model the interactions between the cryosphere, the oceans and the atmosphere during the most recent glacial/ interglacial transition.

Approach: In order to develop a model capable of simulating the climate during this period in the history of the Earth, key components of the climate system must be included. A two dimensional surface energy balance model (EBM, latitude and longitude resolved) is included to model the atmospheric response of the climate system. This type of model compares favorably with atmospheric general circulation models (Hyde, et al., 1989) and is highly recommended for paleoclimatic applications. Next, a latitude/depth resolved upwelling diffusion thermodynamic ocean is included which has a parameterization for the poleward heat transport in the oceans related to

the thermohaline circulation (Morantine, 1993). In order to model this period effectively, an ice sheet model is also required. The ice sheet model selected for this investigation is based on the integrally averaged ice sheet model (latitude and depth resolved) originally presented by Verbitsky and Oglesby (1992).

Variations in the insolation patterns are calculated by the method of Andre L. Berger (1978). The infra-red radiation leaving the system is defined by Graves, et al., 1993, which includes a seasonally varying albedo definition. The influence of variations in CO₂ on the energy budget is handled in a manner similar to Wigley, et al., (1985) by relating the radiative forcing to the concentration of CO₂.

The modeling effort has been designed to take advantage of paleodata sources that define aspects of the system that are not modeled with a great deal of confidence. The CO₂ concentration variations are well documented in ice cores (Barnola, et al., 1987) and are defined to conform with observations. The precipitation field required for the mass balance (DeBlonde and Peltier, 1991) on the ice-sheets are defined based on the Shea Climatology.

The thermohaline strength is also considered to be one of the processes which is not modeled with a great deal of confidence. In this modeling effort, a technique has been developed to define the thermohaline strength in the Atlantic Ocean based on the isotopic signatures in deep sea sediment cores (Morantine, 1993).

Results to Date: The three key components described above (atmosphere, oceans, ice sheets) have quite different time scales. The surface model (EBM) responds to radiative forcing on a time scale equal to approximately 6 years. The exchange of energy between the deep ocean and the surface model occurs on a time scale equal to approximately 50 years (Morantine, et al., 1994). The ice sheet evolves on a much larger time scale which appears to be approximately 10,000 years.

The ice sheet interacts with the surface model by

albedo modification and by altering the surface elevation thus influencing the surface temperature through a lapse rate feedback. The ice sheet interacts with the ocean through melt water runoff and the calving process which influences the thermal energy and salinity in the oceans.

Due to the magnitude of the time scale for the ice sheet, starting with a steady-state profile based on the conditions at 18kya is not satisfactory. By starting the ice sheet from an ice free condition at 125 kya, the ice sheets will grow and respond to the perturbations introduced during the retreat phase of the ice age in a manner more consistent with the paleodata. Attempts to initiate the retreat of the ice sheets from a steady-state profile show a 3 to 5 thousand year lag in the response to changing orbital parameter values and changing CO₂.

Manuscripts in Preparation and Submitted:

Watts, R.G. and Morantine, M.C., "Modeling climate with general circulation models", proceedings of the Thermal Engineering for Global Environmental Protection, U.S./Japan Seminar, July 1995, (to appear).

Morantine, M.C., "Rapid Climate Change", Heat, Mass and Momentum Transfer in Environmental Flows, ed. S.A. Sherif, HTD, 1995, (to appear).

Morantine, M.C. and H.S. Khesghi, "The effect of salinity variations in the world oceans during the most recent glacial/interglacial transition", in preparation.

Presentations:

Climate dynamics. Seventh International Symposium on Measurement and Modeling of Environmental Flows, International Mechanical Engineering Congress and Exposition (IMEC&E 1995). Invited presentation, San Francisco, CA, Nov. 12-17, 1995.

The influence of ocean salinity variations on the air-sea exchange of carbon dioxide during the ice-ages. Tulane University Seminar, March 1995.

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The Minimum Entropy Hypothesis: Can It Be Used to Constrain Climate Models?

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Objective: It has been proposed by a number of scientists that the climate system might seek a steady state in which the global production rate of entropy is extremized. Essex (1984) and others have shown that most of the research on this problem has used a fundamentally incorrect formulation of the entropy production rate because they did not take proper consideration of radiative entropy. Our objective is to test the minimum entropy hypothesis using a series of energy balance climate models and properly formulated radiative entropy production.

Product: The product will be results from energy balance climate models in which various parameters are varied to find those that result in minimum entropy production. For example, the diffusivity in a diffusive energy balance model might be varied and the resulting value compared to that which gives the "correct" poleward transport. Alternatively, several parameters might be examined simultaneously.

Approach: Grassl (1981) briefly noted that if the incoming radiation was associated with solar radiation then the entropy gain by the Earth should be the Solar radiation divided by the temperature of the Sun rather than the local temperature, as is assumed by many authors. He did not pursue the idea, however, instead returning to the (incorrect) formulation of Paltridge (1975). The proper formulation must account for the fact that the radiation field itself has entropy, as pointed out by Essex. If it is assumed that the Earth and its atmosphere act as a black body and the Earth reflects solar radiation as a grey body then the total zonally averaged entropy lost is where is the albedo, Q is the solar constant divided by four, $S(x)$ is the distribution function for solar radiation, T_s is the

solar temperature, T_e is the effective black body temperature of the Earth, and is the Stefan-Boltzman constant. The distribution of temperature is determined by a diffusive zonally averaged energy balance climate model. Once the temperature distribution is obtained, the equation for entropy production can be solved and the entropy production for various values of the poleward diffusivity determined.

Results to Date: We have determined the variation of entropy production with diffusion coefficient. The preliminary results imply that if other parameters remain constant the entropy production is minimized when the poleward diffusivity is zero. We are now in the process of using variational calculus to study the problem as several parameters are changed.

Students: A student, Mr. Si Li is now supported on this grant. In addition, we continue to work closely with Mr. Dan Collins at New York University.

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Regional Atmosphere/Forest Exchange and Concentrations of Carbon Dioxide

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Objectives: The overall goal of the project is to determine, by direct measurements (eddy correlation), the net ecosystem exchange of CO₂ between the atmosphere and a mature mixed forest in northern Wisconsin over at least a full annual cycle, and on a regional scale. The observations are part of an effort to elucidate the role of northern temperate and boreal forests in the global carbon budget. The measurements are being carried out on a 450 m tall television and radio transmitter tower, and represent the largest spatial scale yet addressed by continuous eddy correlation observations. An additional objective of this work is to examine flux-gradient relationships in the planetary boundary layer (PBL) under a range of stability conditions to develop and evaluate methods for monitoring the surface flux using relatively simple and robust methods, such as mixing ratio gradients and meteorological data.

Products: (1) Observations of the overall carbon balance of the regional forest, and investigation of which environmental variables are most important for determining the net carbon balance. (2) An evaluation of how CO₂ concentration data obtained at up to 500 m height on towers can best be used, in combination with data from other sites, and from aircraft, to constrain the terrestrial carbon budget. (3) An evaluation of the usefulness of flux-gradient relationships for calculating surface fluxes of trace gases in long-term monitoring applications.

Approach: The study is being carried out at the WLEF-TV transmitter tower, located in the Chequamegon National Forest in northern Wisconsin. The region is in a heavily forested zone of low relief. The tower is a triangular steel scaffolding structure 447 m tall and with faces 2.1 m wide.

The experimental design is chosen to continuously assess the net ecosystem exchange of CO₂ (NEE) between the atmosphere and the forest, over the largest possible area:

$$NEE = F_h - \langle \text{div}F \rangle,$$

where F_h is the flux of CO₂ through a horizontal plane at height h above the ground, and $\langle \text{div}F \rangle$ is the flux divergence below h . If mean horizontal advection is negligible, $\langle \text{div}F \rangle$ can be estimated using the rate of change of storage (RCS) of CO₂ below h , which can be determined from measurements of CO₂ mixing ratios at several altitudes below h . The RCS term generally integrates to zero over any 24 hour period, but is important for determination of the instantaneous NEE, needed, for example, to determine the relationship between NEE and illumination.

Vertical fluxes of CO₂, water vapor (L), sensible heat (H) and momentum (M) are measured at 76 and 396 m above the ground by eddy correlation. For CO₂:

$$F_h = \langle w'CO_2' \rangle,$$

where w is the component of the wind vector perpendicular to the local stream lines, primes indicate that the time series have been detrended and the means removed, and the brackets indicate time averaging.

A three-axis sonic anemometer is used to measure the wind vector and virtual temperature for flux measurements at each eddy correlation level. The CO₂ and H₂O measurements for eddy flux calculations at each level are made by drawing air through a tube of 1 cm inner diameter, with the inlet mounted near the sonic anemometer, to instruments located in a trailer on the ground. The analysis is carried out by NDIR spectroscopy using a Li-Cor model 6262. Since H₂O and CO₂ are measured in the same absorption cell it is straightforward to accurately correct the CO₂ fluxes for density variations caused by water vapor fluctuations.

The shallow nighttime planetary boundary layer, often no deeper than about 100 m, imposes the necessity of flux measurements at a minimum of two altitudes to observe fluxes at the largest

possible spatial scale for all atmospheric stability conditions. Fluxes measured at 396 m represent fluxes over a large spatial scale during daytime, convective conditions, but that altitude is typically decoupled from the surface when the boundary layer is stably stratified. For that reason, we have also instrumented the tower for CO₂ flux measurements at 76 m.

These measurements are being carried out in cooperation with the Forestry Science Laboratory (FSL) of the USDA Forest Service in Rhinelander, WI. The FSL carries out long-term forest succession and microclimate studies in the Chequamegon National Forest. Measurements of importance to our study that will be made by FSL include forest soil temperature, within-canopy air temperature, and transmitted PAR. FSL also provides assistance with maintenance of the equipment at the tower. The NOAA Aeronomy Laboratory is operating a boundary layer profiling radar and radio-acoustic sounding system (RASS) approximately 8 km from the tower site, in cooperation with our program. The profiler will measure mixing depth, and temperature and wind profiles.

Results to Date: Measurement of CO₂ mixing ratios at 11, 30, 76, 122, 244, and 396 m were begun in October, 1994. Flux measurements (CO₂, H₂O, heat, momentum), at 76 and 396 m, and observations of net radiation at the surface were begun in late April, 1995. Preliminary analyses have confirmed the viability of the experiment design. Carbon dioxide flux data show the start of significant photosynthetic activity about 1 June.

1) Preservation of turbulent signal, noise levels, and lag time: The sonic anemometer observations are made directly at the two levels on the tower, but the CO₂ and H₂O observations are made after pumping air down to the instrument trailer at the base of the tower. In order to preserve the turbulent signal in CO₂ and H₂O through the long tubes (400 m from the top level to the Li-Cor), a very high flow rate is

necessary. The spectrum of the Li-Cor CO₂ signal (Figure 1) shows a shape typical of atmospheric turbulence down to a frequency of nearly 0.1 Hz (wavelength of about 50 m). A more complete picture of the atmospheric inertial subrange is seen in the vertical velocity spectrum, also shown in Figure 1. White noise dominates the CO₂ spectrum beyond 0.1 Hz.

The time lag between the sonic anemometer and the Li-Cor observations must be determined to compute eddy-correlation fluxes. Figure 2 shows the lagged covariance between the vertical velocity from the anemometer at 396 m and the corresponding Li-Cor CO₂ signal. This data is from the same one-hour period as that plotted in Figure 1. The broad minimum at about -85 seconds (denoted by the vertical dotted line) indicates that this time lag can be identified and used to match the two data streams in time. The sharp peak at 0 seconds is caused by correlation between noise in the CO₂ and vertical velocity signals. It is evident that the time lag effectively eliminates white noise from the computed flux.

2) Flux observations: Figure 3 shows the diurnal cycles of CO₂, latent heat and sensible heat fluxes from two days in early May and two more days in early June. The difference is striking as, in early May, deciduous trees had not leafed out, and CO₂ and H₂O fluxes were quite small. Afternoon vertical gradients for CO₂ between 30 m and 396 m were typically very close to zero (for all of May: mean = -0.03 ppmv, st. dev. = 0.17 ppmv) during May, indicating that net fluxes were small, in support of the flux data. By late June, the CO₂ and H₂O fluxes were substantial. Our 76 m flux level, and CO₂ profile measurements at six heights on the tower will allow us to extrapolate the 396 m flux value to a surface flux measurement. Note that at night the 396 m level is generally above the level of mechanical mixing.

Presentations: Monitoring Regional Forest-Atmosphere Exchange of Carbon Dioxide, 22nd Conference on Agricultural and Forest Meteorology, Atlanta, Georgia, January-February, 1996.

Fig. 1: Spectra from 2 June, 13-14 Hours LST

Fig. 2: Lagged Covariance: w and CO₂ - 396m

Fig. 3a: 396 m Level Fluxes, 5-7 May, 1995

Fig. 3b: 396 m Level Fluxes, 1-3 June, 1995

Pilot Study in Integrated Assessment Related to Global Warming

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Objectives:

1. Perform a literature search on previous integrated assessment applications
2. Investigate the feasibility of developing a computer software tool that can be used in a policy making framework. This experience was expected to lead to a more comprehensive proposal to NIGEC.

Products: The literature search was performed and a research proposal was developed and submitted to NIGEC (see attached Executive Summary and Hypothesis).

Approach: The literature search included contacting researchers interested in cotton crop modeling and methane generation from rice paddies (see references). The development of a methodology for applying integrated assessment to the consequences of global environmental change on agriculture was studied to develop the research proposal.

Results to Date: A research proposal on integrated assessment was developed and submitted to NIGEC.

Students: One graduate student was supported by this project.

Executive Summary

The term "integrated assessment" has been coined to describe research efforts involving combination of systems analysis and game theory to provide tools for policy making. Systems analysis includes mathematical modeling, systems identification, process control, and other tools of applied mathematics. Game theory is a branch of economics that allows the inclusion of costs and benefits in a quantitative form for decision making. This project is intended to develop methodology for application of integrated assessment to cotton production under scenarios of global warming. Mathematical models will be combined with

economic estimates to produce a computer software tool. A prototype policy making tool will be the primary deliverable of the project.

Statement of Hypothesis to Be Tested or Questions to Be Answered:

Integrated assessment is a developing methodology for combining systems analysis and economics to provide tools for policy making (Nordhaus, 1993; Gaskins and Weyant, 1993; Dowlatabadi and Morgan, 1993). Systems analysis combines mathematical modeling, system identification, process control, and other tools of applied mathematics into a cohesive approach to explaining complex systems and mechanisms. Game theory is that branch of economics that allows the inclusion of costs and benefits in a quantitative form in a decision making context (Eyckmans, et al., 1993). The proposed work involves the development of a methodology for applying integrated assessment to the consequences of global environmental change on cotton agriculture.

Work on cotton crop modeling began in the early 1970's. The current model, called GOSSYM has been under development since 1984 (McKinion et al., 1989). These prior efforts did not consider extreme variations in climatic condition. A current NIGEC supported effort (Hodges, et al., 1993) is aimed at extending existing models to predict the response of cotton crops to significant increase in temperature (3 to 5 oC) and CO2 levels. The proposed effort involves utilizing the revised model in an integrated assessment framework to provide a tool to policy makers. Methods will be developed for utilizing game theory together with the revised cotton crop model to provide estimates for both the cost of global warming and the benefits derived from proposed mitigation efforts. This will allow quantitative estimates of the economic effects of potential global warming scenarios on cotton agriculture.

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Factors Affecting Formation, Emission and Secondary Reactions of Nitrous Oxide and Methane in the Flooded Soil Profiles of Gulf Coast Wetlands and Flooded Rice Fields

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Objectives: Two important greenhouse gases, nitrous oxide and methane, are produced by biogeochemical reduction reactions in anaerobic systems such as flooded rice fields, landfills, waste treatment ponds, and natural freshwater wetlands. Several studies have demonstrated a temporal segregation in reduction reactions; that is a sequential reduction of O_2 , NO_3^- , manganic Mn compounds, ferric Fe compounds, SO_4^{2-} , and finally CO_2 (or a $-CH_3$ group). Spatial segregation, with increasing reduction intensity with depth, is caused by the continuous input of atmospheric O_2 to the sediment surface. Field studies are not in agreement, systems have been described in which different redox reactions are separated along profile gradients of greater than 40 cm, less than 1 cm, or in co-occurrence. The objectives of our study were to 1) determine depth distribution patterns of N_2O and CH_4 under laboratory conditions, 2) determine gas emissions and leaching losses in gas lysimeters under laboratory conditions 3) determine field gas emission rates, and 4) determine the effect of rice field drainage on gas emission/production/oxidation.

Products: These questions are of fundamental importance in quantifying the role of wetlands as a source of greenhouse gases, in providing baseline data to evaluate the consequences of global climatic change on future greenhouse gas production rates, and in evaluating management options for flooded rice agriculture and other natural and constructed wetlands.

Approach: Both laboratory and field systems were investigated. In the laboratory system, packed soil cores from a rice field and a eutrophic lake were flooded with deionized H_2O and allowed to equilibrate for approximately one year. Cores were then transferred to solution baths containing different concentrations of NO_3^- and incubated for 5d. The headspace above each core was sealed, purged with N_2 , and sampled after 1d. The cores were then frozen, sliced horizontally into one cm sections and the N_2O and CH_4 in each section extracted and analyzed by gas chromatography. The

concentrations of NO_3^- , Mn^{2+} , Fe^{3+} were also determined along the depth gradient to refine our characterization of the oxidation-reduction status profile. Cylinders pushed into the soil of a swamp forest receiving NO_3^- from treated sewage effluent were allowed to equilibrate for 1 wk, removed and frozen with dry ice, and assayed for N_2O and CH_4 profiles.

Gas emissions and dissolved N_2O concentrations were measured from field systems. We developed a gas sampler consisting of an inverted funnel with legs extending radially beyond the mouth of the funnel. Lowering the gas sampler gently onto flooded sediment surfaces resulted in only negligible gas volumes entering the samplers. These samplers can be positioned in any system in which the floodwater depth is greater than the height of the sampler, and can be left for variable time periods (hours to weeks), depending on gas emission rates and water solubilities. Dissolved N_2O was measured by equilibrating H_2O samples with a N_2 headspace.

Results to Date: We developed a laboratory system permitting the assessment of redox reactant and/or product depth distributions and emissions under conditions which can be manipulated. Simultaneous emission of N_2O and CH_4 was noted from whole tubes (Fig. 1), with N_2O emissions stimulated by NO_3^- addition, and CH_4 emissions stimulated by rice straw addition. Decreasing N_2O concentrations and increasing CH_4 concentrations (Fig. 2) occurred with profile depth. Peak concentrations of reduced Mn occurred higher in the soil profile than did peak concentrations of reduced Fe, further supporting the existence of redox reaction zonation.

We identified a field site in which denitrification reactant and product concentrations vary along a 1 km gradient, thus permitting future field studies to be designed. In contrast with our laboratory results, CH_4 concentrations were highest in the surface 1 cm of the profile. Based on other reports in the literature, we interpret this to indicate denitrification probably occurred either

in the H_2O column or only at the immediate soil:H $_2O$ interface; and that the *in situ* profile gradient occurred along a much smaller spatial scale than would be detected with a 1 cm slicing technique. Declines in CH_4 with depth probably correspond to decreasing labile C.

A seasonal, probably temperature-related pattern of CH_4 emissions by lake sediments was detected. Emissions were as high as $10 \mu g CH_4 cm^{-2} d^{-1}$, while laboratory incubations of unamended soils yielded only $5-10 ng CH_4 cm^{-2} d^{-1}$. The long preincubation and lower ($23^\circ C$) temperatures probably led to reduced rates in the laboratory study.

An additional field test of the gas samplers was in $10 m^3$ outdoor fish tanks. The gas samplers detected a decrease in CH_4 production by fish tank sediments when aerators were positioned in the water column. As was observed in our laboratory study, the effect of NO_3^- on CH_4 emissions was minimal.

Publications and Presentations:

- Manuscript submitted to Soil Science Society of America Journal, March 1995. Vertical zonation of N_2O and CH_4 in flooded soil and sediment columns.

- Paper presented at the American Society of Agronomy Southern Branch Meeting; Jan. 30, 1995; New Orleans, LA. Zonation in anaerobic soils and lake sediments: N_2O and CH_4 formation and emission.

- Presentation to be made to Conference on Ecology and Management of Southern Forested Wetlands. Clemson University, Clemson, South Carolina; March 25, 1996.

Figure 1. Emissions of N_2O and CH_4 by Crest Lake sediments exposed to gradients of NO_3^- concentrations with and without supplemental glucose. 1a. The deionized H_2O treatment was assigned a NO_3^- concentration of $0.01 mM$, to permit quantification on a log scale. 1b. Values are means ($n=3$) $\pm$ SE.

Figure 2. N_2O (a) and CH_4 (b) profiles of the Crowley soil and Crest Lake sediment systems. Treatment designations indicate the floodwater NO_3^- concentration (mM) / presence or absence of rice straw as an amendment. For each treatment, the statistical significance of the depth variable in an analysis of variance is indicated by: ns, no significant differences; †, $p < 0.1$; or *, $p < 0.05$. Values shown are means ($n=3$) $\pm$ SE.

Figure 3. Relative extractable Mn and Fe profiles of the Crowley soil and Crest Lake sediment systems. The statistical significance of the depth variable in an analysis of variance is indicated by: *, $p < 0.05$; or ***, $p < 0.001$. Values shown are means ($n=12$) $\pm$ SE of pooled data from different sediment/straw amendment/ floodwater NO_3^- combinations.

Figure 4. (a) Gradients of dissolved NO_3^- and N_2O at the Thibodaux tertiary wastewater treatment swamp forest. Values shown are means ($n=4$) $\pm$ SE. (b) Concentrations of CH_4 along a depth gradient in soils collected 25 m from the wastewater inlet. Data are from 5 replicate cores.

Figure 5. (a) Field emissions of CH_4 by Crest Lake sediments. Numbers in parentheses refer to the mean sediment temperature at the start and at the end of the sampling period. Three replicate samplers were left in position for the entire time period between dates reported. (b) Field emissions of CH_4 by fish tank sediments underlying water columns with or without aerators.

Progress Reports Not Yet Received

Drs. Martin Hoffert and Michael Rampino, New York Univ., Climate sensitivity, paleoclimates and climate-model verification/calibration

Dr. Julia Cole, Univ. of Colorado, Incorporating tracers in the hydrologic cycle of the GENESIS earth system model

Dr. Gerald R. North, Texas A&M, Seasonality and estimation in climate research

Southeast Regional Center

Robert A. Griffin, Director

The Southeast Regional Center of the National Institute for Global Environmental Change (NIGEC) has been in operation since 1991. Located at The University of Alabama, in Tuscaloosa, Alabama, the Southeast Regional Center-NIGEC is striving to be a scientific center of excellence for global climate change data in the Southeast. The Center is charged with the mission of planning jointly with DOE and developing a research and education program in the southeastern region which supports the DOE's tasks within the federal Global Change Research Program through university-based research. The Southeast Region consists of nine states: Alabama, Florida, Georgia, South and North Carolina, Virginia, West Virginia, Kentucky, Tennessee, and the territories of Puerto Rico and the Virgin Islands.

The Center has developed a focus for its project research efforts on the following thrust areas:

- Research on interactions between the atmosphere and major terrestrial ecosystem types in the southeastern U.S. with respect to (1) the impacts of climatic and atmospheric change (particularly increases in atmospheric CO₂) on major terrestrial resources and ecosystems in the southeastern U.S. (e.g., forests, wetlands, managed ecosystems) and/or (2) the quantitative role of major southeastern ecosystems as global sinks or sources of energy-related greenhouse gases, especially CO₂, including the climate feedback effects.
- Improvements in the mechanistic understanding of atmospheric, terrestrial, and marine processes important in climate change, particularly as related to 1) radiative effects of greenhouse gases, aerosols, and clouds on the Earth's climate system with an emphasis on those effects, feedbacks, and processes important in the Southeast U.S., and 2) formulating these effects, feedbacks, and processes into models of climate change at regional and global scales.

As a part of the continuing development of this program, a request for proposals (RFP) for FY94 was issued on October 1, 1993. The call for proposals resulted in a total of 58 letters of intent, with a resulting 49 submissions of which 38 were new proposals and 11 were continuation requests. An excellent distribution of responses was obtained with submissions being received from 24 universities in 11 states. All the proposals funded in 1994 fit into these Regional research thrusts and support the objectives of the Region's research and education program.

Regional Review Process

The Regional review was performed by a Peer Review Panel appointed by the Regional Director in accordance with the Regional Center Management Plan. The Region's Peer Review Panel consisted of sixteen scientists and engineers plus the Regional Center Director who served as Chairman of the Panel. The group met in Tuscaloosa, Alabama on January 13-14, 1994 to evaluate the proposals. The Panel was conducted in the style of a National Science Foundation (NSF) panel, using the NSF scale (Excellent, Very Good, Good, Fair, and Poor). The review process is described in the annual RFP.

FY94 Awards

A total of 15 projects were funded through the regional review process. In addition, the Director's Fund supported two research symposia to enhance technology transfer in the Southeast region.

Director's Fund

Two grants were made from the FY94 Director's Fund after approval by the local program committee. They were:

- Kiene, University of South Alabama
International Symposium on DMSP and Related Sulfonium Compounds (the report for the Kiene project is included in the Research Summaries)
- Griffin, University of Alabama - Tuscaloosa
Annual Southeast Regional Center - NIGEC Research Symposium and Regional Advisory Board Meeting

The Annual Southeast Regional Center -NIGEC Research Symposium was held in Tuscaloosa on April 25-27, 1995 with 66 attendees. The theme of this year's meeting was reducing scientific uncertainty in climate change research. The symposium presented research results from projects currently funded by the NIGEC Southeast Regional Center. Twenty research summaries were presented by principal investigators in the one and one-half day meeting. The symposium also provided a meeting place for investigators to network and to explore current and potential cross-linkages in the various projects. The meeting was also coordinated with both the annual Regional Advisory Board meeting and a scheduled meeting of the NIGEC Board of Trustees. This allowed members of these groups to interact with each other and with researchers to explore new concepts and ideas.

Terminating Projects

The following projects from the Center are terminating this year and are not included in the Research Summaries. These projects will be submitting Final Reports this year.

Chanton, Jeffrey	Florida State University, <i>Control of Methane Flux by Vegetated Wetlands.</i>
Cox, Gregory	University of Alabama - Huntsville, <i>The Ground Truth Studies Program: A Curriculum for Understanding Global Change.</i>
Cutter, Gregory	Old Dominion University, VA, <i>Production and Sea-Air Flux of Carbonyl Sulfide in the Coastal Environment.</i>
Smith, Thomas	University of Virginia, <i>Modeling Patterns of CO₂ Flux from Forest Systems.</i>

Regional Advisory Board Meeting

Following the Center's Management Plan, an annual meeting of the Regional Advisory Board was held on April 25, 1995 in conjunction with the Research Symposium. Major topics covered were an overview of NIGEC and the U.S. Global Change Research Program, RFP and proposal review process, and the NTAC program review and direction. Highlights of this year's meeting were the Recognition Dinner for the Advisory Board with presentation of Service Award plaques to eight Advisory Board members who have completed a three year term of service, and a joint Advisory Board/Board of Trustees Dinner Meeting.

Presentations, Publications, and Student Activity

Activity is indicated in each of the project reports, and a summary of the categories is given in Table 1.

**Table 1. Southeast Regional Center - NIGEC
Presentations, Publications and Student Activity, FY94**

PI	Status	Presentations	Publications			Theses/ Dissertations	Student Activity			
			Published	In Review	In Preparation		PD	D	M	U
Boote	2nd year	1							1	
Brett	3rd year	1							1	2
Chassignet	3rd year	1	1	1		1			1	
Christy	3rd year	4	1		1			1		
Gholz	1st year	1					1	1	1	
Johnson	3rd year	1	1				1	1		
Kidder	3rd year	1	1				1			
Klene	1st year	1								
McNider	3rd year	7	3	1	3		1	1		
Oren	3rd year	3	1	2					4	
Post	1st year	1								
Rogers	3rd year	7	2		2					6
Saxena	3rd year	5	1	1		2			5	
Shure	3rd year	2			1				1	
Weaver	1st year	1								
White	1st year	1		1					2	

Legend: PD = Post Doctorate
D = Doctorate
M = Masters
U = Undergraduate

Research summaries of all the FY94 funded projects follow.

Director's Fund: First International Symposium on DMSP and Related Sulfonium Compounds, by Ronald P. Kiene, Department of Marine Sciences, University of South Alabama

Objectives: To bring together for a symposium the world's top researchers working on the natural sulfonium compound, dimethylsulfoniopropionate (DMSP). DMSP is produced by a variety of plants and algae and its principal function appears to be to alleviate water stress at high salinities or under desiccation. There is currently a great deal of interest in DMSP because it is decomposed to dimethylsulfide (DMS), a volatile form of sulfur which has a global impact on atmospheric chemistry and climate dynamics. There has never before been a conference which has focused on DMSP and it was deemed necessary to bring researchers together to share recent findings and to stimulate interactions.

Products: A highly successful symposium, attended by 66 researchers representing 12 countries (Figure 1). Forty one (62%) of the participants were from outside the US, making this truly an international symposium.

Approach: The symposium's focus was on fundamental aspects of the role of DMSP in organisms and the environment. The symposium consisted of 9 invited plenary talks of 40 minutes duration. These plenary talks were used to lead off sessions of contributed talks (20 minutes each). In total, there were 35 oral presentations and 20 posters. The posters were displayed on boards in the back of the meeting room and were up for the entire meeting. A formal poster session of 2.5 hours was held on the afternoon of the middle day of the symposium. This provided ample time for participants to view the posters and to speak with their authors.

Networking among the attendees was facilitated by an introductory mixer preceding the meeting and a bus excursion to the Dauphin Island Sea Lab.

Results to Date: The results of the symposium can be taken as an increased knowledge of current research being conducted on DMSP that is now shared by all the participants. This knowledge should aid researchers in addressing questions as to what role DMS will play in future climate and global change scenarios. The response of the participants to all aspects of the symposium was overwhelmingly positive. There was a strong general consensus that a *Second International Symposium on DMSP* should be held in the future, probably in Europe. There was even talk of a third symposium and there were a number of volunteers to take on the responsibility for organizing these meetings! This can be taken as evidence of a successful *first* meeting.

Students: Of the total number of participants, 26 (39%) were advanced graduate students. Quite a number of these made outstanding presentations; this suggests a positive future for DMSP research.

Publications: The symposium proceedings will be published by Plenum Publishing Corporation. At this time 30 manuscripts have been submitted for publication in the book which will be entitled, "Biological and Environmental Chemistry of DMSP and Related Sulfonium Compounds". Judging by the quality of submitted manuscripts, the book should become the definitive volume on the subject of DMSP. The book should be in print by early 1996.

Figure 1. Distribution of participants in The First International Symposium on DMSP and Related Sulfonium Compounds by Country.

Carbon Balance and Growth Adaptation of Contrasting C₃ and C₄ Perennial Forage Species to Increased CO₂ and Temperature

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University of Florida

L. H. Allen, Jr. and T. R. Sinclair
USDA-ARS, Gainesville, FL

Objectives:

1. To quantify climate change effects on C and N balance processes of two perennial warm-season forage species differing in photosynthetic pathway.
2. To quantify the long-term effects of elevated temperature at ambient and elevated CO₂ on photosynthesis, respiration, growth, nutritive value, assimilate partitioning, rhizome growth, and carbohydrate storage dynamics in rhizomes/stolons in two perennial warm-season species.

Products: It is important to understand the C balance dynamics of perennial grassland species, particularly under projected increases in CO₂ and temperature: 1) to understand the degree to which these species act as sources and sinks for carbon dioxide (CO₂), and 2) to evaluate effects of climate change on productivity and C sink capacities of these plants. The two perennial warm-season forage species studied include bahiagrass (*Paspalum notatum* Flugge), a C₄ pasture grass predominant in the Southeastern USA, and perennial peanut (*Arachis glabrata* Benth.), a long-lived C₃ forage legume. They are long-lived perennial species that sequester considerable C in underground rhizomes or surface-level stolons, a feature important to understand in modeling C balance dynamics of terrestrial ecosystems. Experiments on these two species under CO₂ and temperature treatments are in progress, and growth and C flux measurements are being obtained.

Approach: This study is designed for evaluation of growth and C balance dynamics of bahiagrass and perennial peanut over a 3-year period at 350 or 700 ppm CO₂ and at temperatures from ambient to +4.5°C in temperature-gradient greenhouses (TGGs). Greenhouse and control system construction was completed by Spring 1995, and the forages were established April 10,

1995. The experiment has two "replicate" TGG's at each CO₂ level, with four temperature sectors (0, 1.5, 3.0, and 4.5°C above ambient) within each TGG.

Four 27-m long TGGs were constructed directly in the field over an Arredondo fine sandy soil. The TGGs are covered with clear polyethylene plastic over galvanized steel support and measure 4.4 m diameter in circular cross-section. Air is moved unidirectionally along four successive 5.5-m long compartments separated by overhead paddle fans to mix air vertically in each successive sector (5.5 m by 4.4 m). Rate of ventilation (and supplemental heating) is regulated to control the temperature gradient from near-ambient in the sector nearest the inlet, increasing in approximate steps of 0.0, 1.5, 3.0, and 4.5°C in successive compartments. CO₂ levels of ambient (nominally 350 ppm) or 700 ppm are maintained by monitoring and injecting of CO₂. Air and soil temperature, CO₂, and growth dynamics are recorded at 4 "sites" along each temperature gradient and at one ambient treatment site outside the TGGs.

Plant growth responses measured over the 3-year study include rate of establishment, shoot growth, rhizome/stolon growth, root growth, forage quality, photosynthesis, respiration, and C and N composition of rhizomes/stolons, roots, and shoots. Leaf, stem, rhizome and herbage samples will be analyzed for N, carbohydrates, and nutritive quality.

Results to Date: More than a year was required for construction of four greenhouses, installation of electrical power, natural gas lines, heating system, irrigation system, CO₂ supply, CO₂-injection lines, CO₂-sampling system, temperature-sensing system, and computer-controlled ventilation system. The heating, ventilation, and CO₂-injection control systems required additional time and expertise for integration. Also, a weather station was set up to document ambient environmental conditions.

The controller/data logger is based on Keithley-Metrabyte hardware and FIX-DMACS software by Intellution. The construction phase took longer than expected, because we needed more engineering support and personnel assistance than was available with NIGEC funding. This additional support was provided by two USDA engineering technicians.

Four TGGs have been completed and CO₂ and temperature control programs developed. The forage species were established April 10, 1995 and the plants are growing well. Because of problems with heater control systems and CO₂-injection valves, the treatment conditions were partial and manually-controlled for the first month. Partial temperature gradient of 1-2°C was achieved immediately with fixed fan speed, without heaters. The CO₂ treatment levels were established May 1 (shortly after significant forage emergence). Beginning May 9, nighttime heating (4.5°C temperature gradients) was established, still with 1 to 2°C gradient during the day. The complete computer program for dynamic, day-and-night control of temperature gradients as well as daytime CO₂-enrichment was initiated June 10. Thus, the CO₂ treatment was effective almost all the time since start of vegetative growth, but the temperature treatment prior to June 10 was only about two-thirds of the desired temperature gradient from cell 1 to cell 4. Nevertheless, the June 7 growth sampling showed responses to both temperature and CO₂.

Experience with the TGGs since June 10, indicates the ability of the system to maintain a 4.5°C temperature gradient from one end of the TGG to the outlet end. The 4.5°C gradient (based on aspirated thermocouples) is controlled very well, with $\pm 0.2^\circ\text{C}$ variability in short-term measurements at night and $\pm 0.7^\circ\text{C}$ variability during the day (the mean is controlled more closely than that). The CO₂ concentration in the CO₂-enriched TGGs is maintained close to 700 vpm during the day and is turned off at night to conserve CO₂ and reduce operational expenses. The short-term variability in CO₂ concentration is ± 70 vpm about the mean of 700 vpm, but it is closer to 700 vpm most of the time. The computer control algorithm is based primarily upon the rate of air ventilation through the TGGs, with proportional and integral control based on a 4-point running average of past CO₂ concentrations (recorded every 30 seconds).

Forage establishment in terms of shoot

emergence, percentage ground cover, and rate of leaf and tiller appearance were recorded for both species. Bahiagrass seedling emergence was mostly complete by April 29, achieving 150-200 plants m⁻². Perennial peanut shoots continued to emerge until May 18, achieved 100-200 shoots m⁻² on May 18, with about two-thirds of the shoots present by April 29. Perennial peanut roots were well nodulated. Percent ground cover initially developed slowly, achieving 10-20% for bahiagrass and 20-30% for perennial peanut by the end of May. Canopy cover developed more rapidly during June.

The first growth samples were taken June 7, about 8 weeks after sowing of seeds or placement of rhizome pieces. Bahiagrass plants ranged from 0.3 to 0.5 g per plant, and averaged 4 tillers per plant and 6 leaves per tiller. There was a clear effect of increased temperature within the TGGs to increase dry matter and leaf area per plant as well as leaves per tiller. Ambient, outside-grown plants were smaller, with about 3 tillers and 5 leaves per tiller, growth-reductions attributed to cooler ambient temperature. Increased temperature also decreased specific leaf weight and root:shoot ratio of the bahiagrass. There was a small increase in mass per plant attributed to elevated CO₂.

On the June 7 sampling, the perennial peanut had accumulated 40 to 100 g m⁻² of dry matter. Increasing temperature across cells within the TGGs, and also from outside-ambient to inside the TGGs, increased total plant biomass, leaf area, and number of shoots. Plants inside the TGGs had 5 to 6 leaves per shoot and those outside had about 4 leaves per shoot, also attributed to temperature difference. Increased temperature caused earlier and more rapid flowering. Elevated CO₂ resulted in greater plant biomass and increased flowering.

We are pleased with the operation of the temperature-gradient greenhouses for control of temperature-gradient treatments and CO₂ levels. The establishment of the forages has been successful. So far, the initial results are consistent with expectations for a C₄ tropical grass and a C₃ warm-season legume, in terms of their response to temperature and CO₂.

During the remainder of this and subsequent seasons, we will continue to evaluate rate of ground cover establishment, growth processes,

forage quality, and C and N sequestering in rhizomes, stolons, roots, and shoots. The next sampling on July 7 will determine the same growth analyses as above, and will also include measurements of CO₂ uptake, canopy dark respiration, and soil CO₂ efflux. Ecosystem C balance will be evaluated by these plant growth measurements and by measuring photosynthesis, respiration, and evapotranspiration of plant canopies, and CO₂ flux from both soil-rhizosphere and fallow sites at 1- to 2-month intervals. Leaf, stem, rhizome and herbage samples will be analyzed for N, carbohydrates, and nutritive quality. Soil organic matter samples were taken at initiation and thereafter, annually. Species growth response to

climate change and the net exchange of CO₂ between plant, soil, and atmosphere will be modeled. An preliminary version of a perennial peanut plant growth model has been developed, based on our CROPGRO model.

Students: One graduate student, Felix Fritsch, has been supported on this project since August 1994. He is conducting his M.S. research on this project and has made major contributions to the study.

Publications: None as yet. Felix Fritsch's M.S. Thesis will be completed in about 1 year, and a paper is planned.

Estimation of Global Warming Based on a Regional Investigation of Physiographic and Cultural Effects on Borehole Temperature Anomalies

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The University of Alabama

Stanley Vitton
Michigan Technological University

Objectives: The objective of this research is to broaden the basis for our previous investigation into the use of subsurface temperature gradients to predict changes in earth surface temperatures, and to model the heat flow causing these temperature changes.

Products: The intent of this work is to continue gathering and implementing subsurface temperature data from a number of sources to (1) increase the statistical reliability of subsurface temperature profiles seen in earlier but limited research, (2) contribute a larger volume of data to the International Heat Flow Commission, (3) study the physiographic and cultural effects of surface land use on the temperature profiles observed, and (4) develop the heat flow model to simulate the conditions observed and to predict past surface temperature through its use.

Approach: The research work performed under this extension required the permission of local coalbed methane operators to grant access to

their wells for temperature data collection. In late 1994, an agreement was reached with Taurus Exploration, Inc., an operation of several hundred wells in the Tuscaloosa area, to use those wells suitable for research. Criteria included conditions that the well had not been completed for production, or altered in any way to disrupt the thermal equilibrium downhole. Taurus provided maps of well locations, and essentially gave our research efforts carte blanche treatment, which allowed us to freely collect data as time and weather conditions permitted. Well data were and are being collected by a department technician, one graduate student, and two undergraduate students supervised by the co-principal investigators.

In spite of the willingness of Taurus to have us log their wells, equipment problems prevented serious data collection prior to March, 1995. The data collected in the previous research program by the outside well logging contractor was

deemed too expensive for continuation in this program, so it was decided to build equipment to log the remaining wells. A surplus winch and single conductor cable remaining from a previous geophysical research project were mounted on a frame which permitted its installation in the bed of a compact pickup truck. The temperature sonde was constructed from an Omega thermocouple, shielded in a PVC sheath to protect it from abrasion in the well casing. Data from the thermocouple were transmitted through the cable to a surface recorder, thence to a computer for observation and storage. The logging equipment was powered by a Honda portable generator.

Problems arose in the amount of electrical noise caused by the electric motor powering the winch as well as a nonlinear depth transducer. Several months were consumed in attempting various repairs and modifications to the equipment. Ultimately, it was decided to abandon the attempt to build equipment and to solicit the loan of proven equipment for collecting test data.

Black Warrior Wireline, Inc., a southeastern U.S. service company offering oil field and coalbed methane downhole services, agreed to loan equipment for use with our winch and cable. This equipment has provided excellent service even though used with the same electric winch. Continued modifications were made to the marginally-useful depth transducer, culminating in a cam-driven counter which has been very reliable and linear in its output. As this report is being prepared, routine well logging is underway at the rate of two wells per working day.

Results to Date: The present equipment allows test data to be read directly into the heat flow model (see discussion below) as digital signals instead of requiring analog-to-digital conversion as previously done. As anomalies in the measured temperature gradient appear, they are checked against open-hole logs taken from the wells at the time of drilling to verify lithology. A typical temperature-depth presentation is shown in Figure 1 for the Sims 13-10 well.

Samples of typical subsurface material were taken from rock cores in nearby wells. These were graded as sandstone, shaly sandstone, sandy shale, shale, "bone" (a carbonaceous shale very dark in color), and coal. These samples were analyzed by Ashworth & Associates, a South Dakota consulting firm specializing in the measurement of rock thermal

properties.

The temperature vs. depth and lithologic data collected in this study are used as inputs to a mathematical heat flow model. The model solves the one-dimensional heat conduction equation in an inverse fashion, and provides the ground surface temperature (GST) during the historical time prior to the time of data collection. The model uses the functional space inverse theory presented by Shen and Beck (1991), and implements that theory within a Bayesian framework in order to overcome problems with ill-posedness of the inverse problem. In effect, the modeling effort recognizes that there are both data errors because of measurement technology and representational errors because of the assumed one-dimensional heat flow in the input data and model itself. Results provided by the model as output are also qualified with their standard errors.

Because the real subsurface environment is heterogeneous in three dimensions, the use of a one-dimensional model can cause spurious noise in inverted GST histories. Recent work by Shen et al. (1994), has been focused on this issue, with the conclusion that one-dimensional modeling is indeed acceptable, provided that certain levels of error are specified for the input data, especially thermal conductivity. When their study results are used, GST histories for all sites in a relatively homogeneous region are remarkably similar. We are presently using their techniques for the data collected previously, with similar results.

Physiographic and cultural data from previously logged sites were collected by a graduate student in geography. Although useful, land-use records were too scant and opinions by family members interviewed were too varied to be statistically significant. As much as it is believed that these land uses affect the temperature history of the area, we could not integrate these factors into the research effort with confidence.

The net results of research, to-date, is that positive temperature anomalies (warming) are observed in the locations logged as is shown in Figure 2. These observations, though preliminary, will be refined through the logging of 20-40 wells over the late spring and summer months and experimentation with the heat flow model. We expect to show that a small but

significant warming effect has occurred over the past 200 years in the west-central Alabama area, and that the quality of the data collected can lead to the modeling of heat flow to simulate this natural process. Further, such data can be used by the International Heat Flow Commission in its efforts to offer widespread information on global environmental change.

Students: One graduate and two undergraduate students worked on this project over the past year.

Papers: No papers other than progress presentations at regional meetings have been presented as yet. The project was covered by a

feature article in a recent issue of The University of Alabama Alumni News magazine. Professional papers are in preparation.

References:

Shen, P.Y., and Beck, A.E., Least Squares Inversion of Borehole Temperature Measurements in Functional Space, *J. Geophys. Res.*, 96: 19,965-19,979 (1991).

Shen, P.Y., Pollack, H.N., Huang, S., and Wang, K., Effects of Subsurface Heterogeneity on the Inference of Climate Change from Borehole Temperature Data: Model Studies and Field Examples from Canada. Paper submitted to *J. Geophys. Res.* (1994).

Figure 1. Temperature versus depth for the Sims 13-10 well.

Figure 2. Ground surface temperature inversion for the 8360-C well.

Heat-Fluxes in a Coupled Atmosphere-Atlantic Ocean Model in Response to Variations in Imposed Temperature Gradients

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University of Miami, RSMAS

Objectives: To couple an idealized general circulation model of the global atmosphere to a multi-layer isopycnal model of the North Atlantic Ocean, and to investigate the properties of the coupled model. The ultimate goal of the project is to quantify the sensitivity of the meridional heat-fluxes in each component of the coupled model to changes in the radiatively forced meridional temperature gradient. We also wish to test how well the equilibrium climate response to a fixed forcing can be predicted from the transient climate response to continuously changing forcing.

While the main focus of our project is on how the coupled model responds to changes in climate forcing, we are also pursuing other issues of interest, such as the nature of air-sea interaction in integrations with fixed forcing, and internal heat budgets in the atmospheric and oceanic models separately.

Product: The products of this project are Fortran programs for integrating various versions of the coupled model and analyzing its output, long data sets generated by the models, and scientific publications which present and interpret the results.

Approach: Observational studies of total meridional heat flux show a rough equipartition between the atmosphere and the ocean. This suggests a coupled-modelling approach for an investigation into the nature and sensitivity of the fluxes. We have configured coupled models from two different versions of a multi-layer isopycnic-coordinate model of the Atlantic Ocean, and a global spectral model of the atmosphere. The coupling procedure was described in our first annual report.

Our experimental approach is firstly to integrate the coupled model and parallel uncoupled models over a long period with seasonally-varying forcing only. Analysis and comparison of these "control" climates allow preferred patterns of air-sea interaction to be found, and allow intrinsically coupled models of variation to be distinguished from models that are internal to

either the atmosphere or ocean.

Secondly, long integrations of both the coupled and uncoupled models are performed in which the seasonally-varying forcing steadily increases over time. Analysis and comparison of these "transient" experiments allows the sensitivity (especially of heat-fluxes) in the coupled model to be measured against the sensitivity of each component separately.

Results to Date: The principal result documented in O'Brien and Chassignet (1995) is that large-scale air-sea interaction in mid-latitudes is dominated by atmospheric forcing of the ocean (in contrast to the tropics where it is well-known that the situation is reversed). The principal interaction pattern that is generated in the coupled model also appears qualitatively when the ocean is forced by a time-dependent atmosphere, but does not force the atmosphere in return. The interaction pattern is related to the classical "index cycle", and has been found in observational data by Wallace et al., 1990. The pattern consists of a simultaneous strengthening (or weakening) of the mid-latitude westerlies and sub-tropical easterlies in the atmosphere, and a cooling of the ocean beneath the stronger winds (or warming beneath weaker winds). Oceanic temperature anomalies of the opposite sign occur at latitudes between the westerly and easterly wind belts.

The principal result documented in O'Brien and Horsfall (1995) is that ocean heat storage is controlled much more by mixed-layer thickness than by mixed-layer temperature. An increase in wind forcing has the counter-intuitive effect of increasing heat storage in the ocean by a mechanical deepening of the mixed layer. This overwhelms the thermodynamic effect of the stronger winds which is to cool the ocean. Climatological data from the north Atlantic and Pacific oceans serve to support the model results.

The sensitivity of meridional heat-fluxes in the coupled model is very different from each of the uncoupled atmosphere and ocean models

separately. Meridional heat-fluxes in the atmosphere are much less sensitive in the coupled case because the task of transporting heat is now partitioned between the atmosphere and the ocean. One shortcoming in these experiments, which has made us reluctant to submit the results for publication, is that transports in the oceanic component were rather weak (by a factor of 5 or so compared with observation estimates). Consequently, we have substituted our mid-latitude ocean model with a more advanced version of the same basic model. The new version extends far into the south Atlantic, has more complete physical parameterizations, and exhibits stronger meridional heat transports.

Students: Student Yan Song was supported by this NIGEC project. He has helped with our analyses, and for his own M.S. project has studied heat-fluxes in the atmospheric model alone. He found that the model circulation switches into a fascinating equatorial superrotation regime (i.e., with strong upper-level westerlies in the tropics) as the radiative driving is increased. He has verified the physical basis

of this phenomenon using higher resolution models and simple theory. He graduated with an M.S. in May, 1995. The title of his thesis is Equatorial superrotation and its maintenance.

Student Fiona Horsfall was not supported by this project, but has collaborated with us to the extent of being a co-author on a manuscript which is currently under review at the *J. Geophys. Res.*

Publications:

O'Brien, E.W., and E.P. Chassignet, 1995: "Extratropical large-scale air-sea interaction in a coupled and uncoupled ocean-atmosphere model", *Climate Dynamics*, in press.

O'Brien, E.W., and F. Horsfall, 1995: "Sensitivity of the heat budget in a mid-latitude ocean model to variations in atmospheric forcing", submitted to the *J. Geophys. Res.*

References:

Wallace, J.M., C. Smith and Q. Jiang, 1990: Spatial patterns of Atmosphere-Ocean interaction in the Northern Winter", *J. Climate*, 3, 990-998.

Exchanges of Energy and Radiatively Active Gases between Slash Pine and Cypress Ecosystems and the Atmosphere in the Southeastern United States

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Objectives: The physical and temporal "scaling up" of process-level information obtained from sensor, chamber, and cuvette measurements to accurately estimate ecosystem- and landscape-level exchanges of energy and matter is a substantial challenge. Although considerable process-level data and numerous ecosystem-level models exist for forests in the southeastern United States (e.g., Slash Pine Model (SPM); Cropper and Gholz 1993, 1994), independent validation data sets are rarely available for comparison with model predictions. The

objectives of this research are to: (1) estimate and compare net ecosystem exchanges of energy, H_2O , CO_2 , CH_4 , and non-methane hydrocarbons (NMHC) from a slash pine forest site and an adjacent cypress swamp site using eddy covariance and condition sampling techniques, (2) modify and validate existing models and develop new models to scale up process-level information obtained from chamber and cuvette measurements of vegetation and soil to estimate net ecosystem fluxes of H_2O , CO_2 , CH_4 , and NMHC, and (3) evaluate model

predictions using net ecosystem exchange estimates.

Products: Ecosystem-level estimates of the net exchanges of energy, H_2O , CO_2 , CH_4 , and NMHC will be obtained for slash pine and cypress pond sites for comparison to model predictions. Once the SPM, CH_4 , and NMHC exchange models are modified and validated, they will lead to an increased understanding of the physical and biological processes controlling net ecosystem exchanges, and can then be used to predict net ecosystem exchanges of energy, H_2O , CO_2 , CH_4 , and NMHC from two of the major ecosystems in the Lower Coastal Plain landscape under simulated climate change scenarios.

Approach: Net ecosystem exchanges of energy, H_2O , CO_2 , CH_4 , and NMHC will be measured using eddy covariance and conditional sampling ("relaxed eddy accumulation") techniques at a slash pine forest site and a cypress pond site. Energy exchanges will be measured using standard meteorological instruments and a sonic anemometer mounted above the canopy on towers, H_2O and CO_2 will be measured with a Licor 6262, CH_4 will be measured using Tedlar bags and GC-FID, and NMHC will be collected using TENAX adsorption tubes and a GC-MS/GC-FID detection system.

The SPM and a multi-layer hydrology model will be modified to incorporate chamber and cuvette flux measurements of H_2O , CO_2 , CH_4 , and NMHC from vegetation, forest floor, and soil. The SPM and submodels will be driven by meteorological and environmental measurements from the tower and soil layers. Model output will be adjusted and validated with a subset of above-canopy measurements.

Results to Date: We measured net ecosystem exchanges of energy, H_2O , and CO_2 above the slash pine canopy during our initial campaign in May, 1995. All measurements were made during dry-canopy conditions, and mean transpiration (T) rates were 2.0 mm H_2O day⁻¹ and 1.2 mm H_2O day⁻¹ for two measurement periods. Rates of T were a nearly linear function of photosynthetically active radiation (PAR) (Figure 1), and little effect of vapor pressure deficit (VPD) on T rates was noted (in contrast to evaporation rates from a wet canopy). Net CO_2 exchange was also strongly controlled by PAR

(Figure 2). Nighttime net CO_2 exchange rates were more variable, and likely reflected periodic "ventilation" of the air space below the canopy (Figure 3).

The SPM was then used to predict the exchanges of energy, H_2O , and CO_2 from the slash pine ecosystem. Both needle phenology and seasonal changes in LAI are calculated by the SPM, and we calibrated predicted phenological and structural parameters using biomass measurements, PAR attenuation measurements, and litterfall data from the site. The SPM underestimated net ecosystem CO_2 emissions at low PAR values, and also underestimated net CO_2 assimilation at higher PAR values (Figure 2). These initial results are consistent with the facts that the biomass of live, respiring tissue, particularly fine and coarse root biomass, were underestimated in the model (Figure 3), and that LAI values were underestimated because the understory was not explicitly modeled. We are currently modifying the SPM to incorporate these factors.

In preparation for CH_4 and NMHC flux measurements to be made using conditional sampling techniques later this year, we have sampled CH_4 fluxes from the soil using chambers, and sampled NMHC concentrations in ambient air above the canopy (Table 1). NMHC concentrations are within the range of those sampled by Johnson et al., (unpublished data) at a site ca. 2 km from our slash pine site.

Students: K. Clark (a recent Ph.D. graduate from UF) has been hired to coordinate and supervise the field sampling; H. Loescher (M.A. student) has been hired to assist with routine sampling and monitoring of speciated non-methane hydrocarbon (NMHC) emissions from broad-leaved species at both sites; S. Lui (Ph.D. student) has been hired to assist with H_2O and CO_2 flux estimates at the Cypress swamp site.

Publications:

Clark, Kenneth L., Wendell P. Cropper, Jr., and Henry L. Gholz. "Exchanges of energy and radiatively active gases between slash pine and cypress ecosystems and the atmosphere in the southeastern U.S." NIGEC Second Annual Research Symposium, Reducing Scientific Uncertainty II, April 26-27, 1995, Tuscaloosa, Alabama.

Figure 1. Transpiration rate as a function of PAR measured above a slash pine canopy using the eddy covariance technique.

Figure 2. Net ecosystem exchange of CO_2 as a function of PAR measured above a slash pine canopy using the eddy covariance technique (closed circles), and estimated using the SPM (open triangles). Two estimates of LAI were used for the SPM simulations.

Figure 3. Nighttime net ecosystem exchange of CO_2 as a function of ambient air temperature measured above a slash pine canopy using the eddy covariance technique (closed circles), and estimated using the SPM (open triangles). Two estimates of LAI were used for the SPM simulations.

Table 1. Selected nonmethane hydrocarbons measured above a slash pine canopy during midday in June, 1995. All concentrations are in pptv.

Compound	Concentration (pptv)		
	Mean	S.D.	Range
α -Pinene (n=6)	183.7	43.9	145 - 250
β -Pinene (n=5)	78.2	9.8	68 - 89

Climate Model Validation Using MSU Global Temperatures

John R. Christy, P.I.
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Objective: The objective of the funded research is to utilize high-precision satellite microwave measurements of atmospheric temperature as a base for validation and analysis of output from global climate models involved in the Atmospheric Model Intercomparison Project (AMIP) being carried out at Lawrence Livermore National Laboratory (LLNL).

Product: The study will produce scientific research reports (utilized in assessments such as the IPCC), journal articles and a Ph.D. thesis which document the comparisons for each model of AMIP. These results will be provided to the

AMIP scientists, the P.I.'s of the individual general circulation models and the NIGEC administrators. These products are key components in evaluating the confidence one may place in the output of the climate models and therefore provide a measure of utility these models bring to the policy-making arena.

Approach: The Microwave Sounding Unit data have been shown to provide measurements of the highest precision for global climate change studies of the atmospheric temperature to date. (Spencer and Christy, *Science*, 247:1558-1562; Spencer and Christy, *J. Climate*, 5:847-857;

Spencer and Christy, *J. Climate*, 5:858-866). With their global coverage since 1979, these data overlap the period of time investigated by the 30+ models of AMIP. The models are required to generate geopotential heights at 850 and 200 hPa, thereby providing the information necessary to calculate the atmospheric thickness between these levels. It is this thickness quantity that is very highly correlated with the MSU weighting function and which will form the model data base for the various comparisons. Several statistical methods will be employed for the comparisons, i.e. correlations, principal component analysis, spectral analysis etc., to determine the fidelity of the individual model fields to the real world.

Results to Date (94-95): Mr. Justin Hnilo, a graduate research assistant to the P.I. in the Atmospheric Science Program of UAH, is being supported under this project. He had an extended visit to the National Center for Atmospheric Research (Boulder CO) in the past year to utilize the NCAR facilities and scientific expertise. Dr. James Hurrell, NCAR Scientist, also serves on Mr. Hnilo's Ph.D. Committee. Mr. Hnilo has begun the written portion of his thesis work in anticipation of completing it under the NIGEC extension at which time publications to refereed journals will be submitted.

The most interesting results obtained in the past year are the comparisons between the magnitudes of model variance versus those of the observed data. As the averaging period lengthened, most regions in the models' climate revealed much greater or much less variability than occurs in nature, particularly in agricultural regions of the northern mid-latitudes (Figure 1). This may be erroneously interpreted in greenhouse gas simulations as a prediction of more severe climate states in the case of greater than observed variability.

Additional results of the past year indicate many climate models portray the atmosphere as coupled to surface temperatures to a higher degree than is observed. An example is displayed in the correlation map of surface temperature versus tropospheric temperature for the ECMWF model (Figure 2).

IPCC Activity: Within the past year, Dr. Christy was selected as a "Key Contributor" to the Intergovernmental Panel on Climate Change - The 1995 Scientific Assessment for chapter 3 "Climate Observations". In addition, he was selected as a contributor to chapter 5 "Climate Models - Validation" for which the current NIGEC research was solicited. No other documents have a greater impact on policy-makers than the IPCC reports. For U.S. scientists, participation in these drafting sessions is funded out of existing grants, which for Dr. Christy was the NIGEC contract. Meetings in Melbourne, Australia and Asheville NC were made possible through NIGEC. A paper, which was written as an outgrowth of the drafting sessions, is now "in-press" and credited to NIGEC support.

Publications:

Christy, J.R., 1995: "Temperature above the surface layer", *Climatic Change*, (in press).

Manuscripts in preparation: Hnilo, J.J., 1995: "Climate Model Validation using MSU Global Temperatures." Ph.D. Thesis.

Presentations-to-date: (Published in Conference Proceedings)

Hnilo, J.J. and J.R. Christy, 1995: "Results of MSU Comparisons", AMIP Workshop, 15-19 May 1995, Monterey CA.

Christy, J.R. and J.J. Hnilo, 1994: "Comparison of GCM and MSU temperatures for the AMIP experiment (1979-88)", Proc. Sixth Conf. Climate Variations, 24-28 January 1994, Nashville TN.

Christy, J.R. 1993: "Global warming not found in high precision satellite temperatures", Proc. Changing Environments: How vulnerable are we? 14-15 October 1993, Indiana University (invited).

Figure 1. Map of the ratio of variance between ECMWF model simulated MSU channel 2 temperature and actual MSU observations. Numbers greater than 1 indicate the model has greater variance than is observed for anomalies lasting a year. Contour intervals are 0.75, 1.0 (thickest line), 1.5, 2.0, 2.5, etc.

MSU 2 correlated with IPCC surface temp

ECMWF

Monthly Values

Thickness correlated with Surface Temp

Figure 2. (top) Gridpoint correlation (x10) of monthly anomalies between IPCC surface temperature observations and MSU channel 2 observations. [e.g. 7 : 0.7, + : 0.0 to 0.35, - : <0.0] (bottom) Correlation between model surface temperature and model troposphere. This is a measure of the connectivity between the surface forcing and the atmospheric response. For this ECMWF model, many values are greater in the model than observations over the ocean, but less over land.

Hydrocarbon Emission from Southern Pines and the Potential Effect of Global Climate Change

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University of Florida, Gainesville

Objectives: The objectives are to determine: 1) accurate emission rates of hydrocarbons, a measure of the tree carbon physiology, as affected by temperature and organ (foliage and stem) over a range of different aged loblolly and slash pine trees, and; 2) an understanding of how the carbon physiology of these pines are affected by proposed climate changes of elevated temperature and ozone, drought, and doubling of CO₂.

Product: Provide a clear understanding of the changes in carbon physiology (by measuring biomass accumulation and distribution, and hydrocarbon emissions) as affected by species, ontogeny, phenology, and organ area under existing environmental conditions as well as under several expected future environmental stresses.

Approach: The research consists of two interrelated studies. One employs controlled environment and branch cuttings from various aged trees of loblolly and slash pine to determine the hydrocarbon emission rates, both quantity and quality, as affected by temperature, phenology and ontogeny. The second study uses open-top chambers to study the effects of proposed climate changes of elevated CO₂, temperature, ozone and drought on the carbon physiology of these two pine species. The carbon physiology responses to these environmental changes include biomass accumulation and distribution over time, net photosynthesis and respiration sampled periodically and hydrocarbon emission rates. This study is planned to span at least three years to be able to determine long-term effects of these environmental factors on the carbon balance of these southern pines.

Results to Date: In study 1, we have characterized the environmental and developmental controls that affect hydrocarbon emissions from loblolly and slash pine. We have completed the study and found significant effects by all of the treatments. A detailed sampling conducted monthly beginning in June 1994 substantiated earlier measurements which

showed a large seasonal effect (normalized for temperature differences). Emission rates from loblolly and slash pine foliage increased from June to a maximum in July and then declined to low levels by September in loblolly and by December in slash pine. The differences between minima and maxima were 5-fold in slash pine and nearly 10-fold in loblolly pine.

In study 2, we are using open-top chambers to expose trees of both species to elevated temperature and CO₂, and drought. The treatments of drought (withholding of every third rain event) and elevated temperature (+3°C) were initiated on May 26, 1992. From May 26 through October 26, the control chambers received 74 cm of simulated rain while the drought treatment chambers received 54 cm (71 percent of the control). The elevated CO₂ (ambient+150 ppm) treatment was started in February 1994, coincident with replanting of half of each chamber with one-year-old seedlings. This allows us to compare the response between "established" trees and younger trees. We are using biomass accumulation and distribution, gas exchange measurements associated with hydrocarbon emissions as physiological response variables. This report summarizes the results through the January 1995 harvest.

The growth response of the trees to the treatments was dramatic. Biomass accumulation was depressed by drought (both ages of loblolly and older slash) and elevated temperatures (younger loblolly and older slash)(Figure 1). Stem and needle biomass were stimulated in the high CO₂ treatment.

The treatments appeared to have the greatest effect on leaf area ratio (LAR) and specific leaf area (SLA)(Figure 2). Consistently, drought increased and CO₂ decreased LAR (elevated temperature and ambient control were intermediate) as a result of decreased and increased total shoot biomass, respectively. Also contributing to these findings were respective reduction and enhanced leaf area in these two treatments. SLA is a measure of needle thickness; the higher the SLA, the thinner the

needle; high temperature and drought significantly increased SLA loblolly pine whereas slash pine exhibited higher SLA in the control and drought in the younger trees only.

Another response found was that elevated CO_2 increased the production of stem units (number of nodes) in subsequent shoot flushes (Figure 3). The younger plants did not show consistent responses to the treatments (Figure 3A and B), but in the older trees, there was a marked increase in stem units under CO_2 and decreases in elevated temperature and drought. Slash pine produced 1 fewer flushes under high temperature (3 vs. 4) while loblolly had 1 less flush under drought (5 vs. 6).

Terpene emission rates sampled coincident with the January harvest showed little treatment effect. From study 1, we know that this is a time of low terpene emission, regardless of temperature.

Photosynthesis measurements made to determine if these pine species down-regulate under elevated CO_2 showed no such regulation when measured in March of 1995. Measurements are continuing through this year.

Students: Jo-Chun Kim, doctoral student, Department of Environmental Engineering Sciences. Tentative completion date: July 1995.

Publications: Kim, J.C., E.R. Allen and J.D. Johnson. Terpene emissions in a southeastern pine forests. *Air & Waste Management Association*. In press.

Visiting Scientist: Roberto Tognetti, National Research Council of Italy, Institute of Forest Tree Breeding and Institute of Remote Sensing, Florence, Italy, was awarded a one year research fellowship working on global change research with Jon Johnson.

Figure 1. Biomass components of loblolly (A and C) and slash (B and D) pine (two ages: upper - 2 yrs. old; lower - 4 yrs. old) exposed to: A - ambient; D - drought; T - elevated temperature, and; C - elevated CO_2 .

Figure 2. LAR and SLA of loblolly (A and C) and slash (B and D) pine (two ages: upper - 2 yrs. old; lower - 4 yrs. old). Treatments are same as Fig. 1.

Figure 3. Number of stem units produced by each flush of loblolly (A and C) and slash (B and D) pine (two ages: upper - 2 yrs. old; lower - 4 yrs. old). Treatments are same as Fig. 1.

Urban Warming: A Satellite, Modeling, and Climatological Study

Stanley Q. Kidder and Jan Hafner
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Objectives: With increased concern about global warming, the need to assess long-term temperature trends has become important. This requires the removal of the urban warm bias from temperature records. The "conventional" measure of the urban heat island magnitude is based on comparison of rural and urban temperature readings which does not account for variability due to different locations of stations, nor does it allow an understanding of urban influence on other variables, such as humidity. The objective of this study is to understand the spatial and temporal evolution of an urban heat island accounting for the net effect of urbanization, i.e. eliminating major uncertainties in urban heat island determination.

Products: (1) A detailed understanding of the development of a particular case of urban heat island, (2) a methodology for initializing mesoscale models of urban areas with satellite data, (3) an understanding of how clouds and wind influence the urban heat island effect.

Approach: A modeling approach is capable of estimating the net effect of urbanization. The idea was first introduced by Hjelmfelt (1982) and is based on a comparison of two numerical simulations of an urban-rural complex. The first simulation is carried out with the urban area included; the second model simulation is run with urbanized areas replaced by natural land use/cover. The difference between these two model outputs is attributed to the net effect of urbanization. The urban area is described by characteristic values of albedo, surface roughness, thermal inertia and moisture availability. The model developed by Pielke (1974), and Pielke and Mahrer (1975, 1978) was used to perform numerical simulations. This model is a hydrostatic, three-dimensional, primitive-equation model with detailed boundary layer and surface energy balance parameterizations. The main factors controlling the urban heat island magnitude are soil thermal properties, soil moisture, and albedo. The values of albedo can be directly retrieved from satellite data; the soil properties have to be determined by Carlson's (1981) method that

utilizes satellite data and model output. The city of Atlanta and clear sky dates of 25 and 26 February 1988 were selected for model simulation over a 200 x 200 km domain (5 km grid spacing) centered at the Atlanta airport. AVHRR satellite data (channel 1) were used to obtain values of albedo in each grid box. The split window technique was applied to AVHRR thermal channels 4 and 5 to retrieve skin surface temperature fields for daytime (4 PM) and nighttime (4 AM) satellite passes. Temperature fields were used to initialize the model and, more importantly, to apply Carlson's technique. The magnitude of the urban heat island was determined as the difference between urban and non-urban simulations. The non-urban case was achieved by replacing the values of albedo, thermal inertia, moisture availability, and surface roughness corresponding to the urban area by values from Atlanta's surroundings.

A second approach involves studying climatological data to determine what happens to urban-rural differences when it is cloudy and satellites cannot view the area.

Results to Date: Figure 1 shows the horizontal field of thermal inertia for Atlanta on 25 and 26 February 1988 derived by Carlson's (1981) method. The increased values over the city are typical of urban environments. Numerical simulation reveals the temporal and spatial development of Atlanta's urban heat island (Figure 2). The maximum horizontal extent occurred at about midnight; thereafter the magnitude and spatial extent slowly decreased. After sunrise the urban heat island diminished rapidly; by the noon it was almost nonexistent. During late afternoon, and especially after sunset, the urban heat island rapidly recovered to its original magnitude and spatial extent. The maximum magnitude (at 2-m height) was determined to be about 1 C at downtown and airport locations.

The climatological study has revealed that wind and clouds substantially change the urban-rural temperature difference. A paper on these results has been accepted for publication (see below). These results indicate that the modeling study

must be extended to consider both windy and cloudy conditions.

Students: Jan Hafner (50%) has passed the qualifying examination and is working on his dissertation.

Publications: Kidder, S. Q., and O. M. Essenwanger, 1995: The effect of clouds and wind on the difference in nocturnal cooling rates between urban and rural areas. *Journal of Applied Meteorology*, in press.

References: Carlson, T. N., J. K. Dodd, S. G. Benjamin, and J. N. Cooper, 1981: Satellite estimation of the surface energy balance, moisture availability and thermal inertia, *J. Appl. Meteor.*, 20, 67–87.

Hjelmfelt, M. R., 1982: Numerical simulation of the effects of St. Louis on mesoscale boundary-layer airflow and vertical air motion: simulation of urban vs. non-urban effects, *J. Appl. Meteor.*, 21, 1239–1258.

Pielke, R. A., 1974: A three-dimensional numerical model of the sea breezes over South Florida, *Mon. Wea. Rev.*, 102, 115–139.

Pielke, R. A., and Y. Mahrer, 1975: Representation of the heated planetary boundary layer in mesoscale models with coarse vertical resolution, *J. Atmos. Sci.*, 32, 2288–2300.

Pielke, R. A., and Y. Mahrer, 1978: Verification analysis of the University of Virginia three-dimensional model prediction over South Florida for 1 July 1973, *Mon. We. Rev.*, 106, 1568–1589.

Figure 1. Thermal inertia ($\text{cal cm}^2 \text{K}^{-1} \text{sec}^{-1}$) determined by Carlson's method (Carlson et al., 1981) for 25 February 1988. Note elevated values of thermal inertia over the urbanized area with a maximum of 0.036 as compared to the value of 0.030 that is typical of the surrounding area. The city of Atlanta is outlined by a thick line and marked with the location of the Atlanta Airport. The extreme value of thermal inertia of 0.041 located just northeast of Atlanta is Lake Sidney Lanier.

Figure 2. Temporal evolution of the modeled urban heat island at a downtown location of Atlanta. The magnitude of the urban heat island is determined as the difference of urban and non-urban numerical simulations for 2-m height temperature (curve A) and skin surface temperature (curve B).

Modeling the Coupled Ocean/Katabatic Wind Systems of the Antarctic with Implications to the Earth's Climate System

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Objective: To develop numerical and analytical models of the coupled atmospheric/ocean/ice systems of the Antarctic to improve our understanding of the regional climate of the Antarctic and to evaluate and improve parameterized processes in General Circulation Models (GCMs) for the region. The Antarctic has played a central role in global change scenarios from melting of west Antarctic ice caps to the Antarctic ozone hole. The Antarctic is unique in that the elevated plateau of the west Antarctic produces extreme katabatic flows which dominate the circulation of the continent and nearby Southern Ocean. We know relatively little about the role these katabatic circulations have on the Earth climate system but, preliminary analyses have shown the katabatic system is important to the initiation and strength of the circumpolar vortex (which is a condition for the development of the ozone hole) and to the circulation of the Southern Ocean and bottom water formation.

Product: Fine scale numerical and analytical models which can be used to evaluate and guide the development of coarse and lower-order GCM simulations of the Antarctic/Southern Ocean climate system.

Approach: The project is centered around developing and applying coupled mesoscale atmospheric/ocean/ice models for the Antarctic katabatic system. Both numerical and analytical models are being utilized. Numerical models are being employed to simulate the complex coupled systems to calculate fluxes and circulations, the results of which can then be compared to GCMs.

Results to Date: During the first two years of the project preliminary coupled atmosphere ocean simulations were carried out and were discussed in previous reports. In summary, for the case of the ice free ocean, the ocean model was run using the windstress produced by the atmospheric model. While the early direct offshore component initially drove a weak near

surface flow offshore, the ocean responded primarily to the along-shore atmospheric component. This along-shore wind stress lead to onshore flow in the surface layer of the ocean. Because of the atmospheric jet structure in the along-shore direction, the corresponding curl produced downwelling in the ocean shoreward of approximately 100 km and upwelling from 100-300 km offshore. The sea surface sloped upward to the coast due to the Ekman dynamics. This led to an offshore directed pressure gradient that produced a substantial along-shore geostrophic current. Strong downward vertical velocities developed at the shore due to the boundary effect and partially due to the curl in the wind stress. A more complete discussion of the model and results were given in earlier reports.

During this third year, comparisons have been made between the numerical model results and those of the analytical models developed in the previous year (see last year's report for a detailed description of the analytical model). The numerical models displayed excellent agreement with the analytical models and results of the comparison are shown in Figure 1. In addition, simulations have been performed to examine the evolution of the zonal wind stress predicted by the mesoscale model for both an ice free and a partially ice covered coastal ocean. Preliminary comparisons between the mesoscale model and a GCM show that the strong polar easterlies that are predicted by the mesoscale model are absent in the GCM results (Figure 2). The strong curl in the wind stress produced by the transition from the midlatitude westerlies to the polar easterlies is an important factor in the forcing of the Southern Ocean. The upwelling induced by this wind stress distribution is responsible for supplying the nutrients that support the high biological productivity of the region. An analytical model based on steady state Ekman dynamics is used to diagnose the upwelling produced for various model derived wind stress distributions (Figure 3).

A simple dynamic ice model has been incorporated into the numerical ocean model. Current efforts are directed toward the inclusion of thermodynamics within the ice model. We expect to carry out simulations of coastal polynyas by the end of summer 1995.

Presentations:

McNider, R.T. Initial Coupling of Katabatic and Ocean Models-Goddard Space Flight Center, August 1992.

McNider, R.T. Modeling the Coupled Ocean/Katabatic Systems of the Antarctic with Implications to the Earth's Climate System-International Conference on Sustainable Development-New Delhi, India, January 1993.

McNider, R.T. Modeling the Coupled Ocean/Katabatic Systems of the Antarctic - NSF Frost Workshop, Ohio State University, August 1993.

Davis, Anthony. Spin-up of the Southern Ocean due to Katabatic Winds, Albuquerque, NM, November, 1993.

Goodrick, S.L. Modeling of the Coupled Katabatic/ Ocean and Ice Systems of the Antarctic - Fourth Conference on Polar Meteorology and Oceanography, Dallas, TX, January, 1995.

Goodrick, S.L. Modeling of the Coupled Katabatic/ Ocean and Ice Systems of the Antarctic - XXI General Assembly of the International Union of Geodesy and Geophysics - Boulder, CO, July, 1995.

Publications:

R. T. McNider, 1993: Modeling the coupled ocean/katabatic systems of the Antarctic with implications to the Earth's Climate System. Proceedings of International Conference on Sustainable Development. Centre for Atmospheric Science, Indian Institute of Technology.

S. L. Goodrick, D. England, and R. T. McNider, 1995: Modeling of the Coupled Katabatic/Ocean and Ice Systems of the Antarctic. Fourth Conference on Polar Meteorology and Oceanography. 174-179.

Figure 1. Comparison of numerical ocean simulation to analytic model. A) Offshore velocity, B) Alongshore velocity and C) Isopycnal surface displacement. Results are shown for 1, 3 and 6 days of simulation.

Figure 2. Comparison of zonal wind stress distribution between the ECMWF GCM and the mesoscale atmospheric model.

Figure 3. Ekman vertical velocities predicted from the wind stress distributions given in Figure 2.

R. T. McNider, and S. L. Goodrick, 1995: Modeling of the Coupled Ocean/Katabatic System of the Antarctic. Accepted to *Antarctic Journal*.

Manuscripts: Davis, A. M. J., and R. T. McNider, 1995: The coupling of Antarctic katabatic winds and the coastal ocean. Submitted to *J. Physical Oceanography*. 1995.

McNider, R. T., S. L. Goodrick, and A. M. J. Davis, 1995: Numerical Modeling of Coupled Katabatic Flow - Ocean Interaction in the Antarctic Part I: Model Description and Evaluation. To be submitted to *J. Physical Oceanography*. 1995.

Goodrick, S. L., R. T. McNider, and W. W. Schroeder: Numerical Modeling of Coupled Katabatic Flow - Ocean Interaction in the Antarctic Part II: Simulations. To be submitted to *J. Physical Oceanography*. 1995.

McNider, R. T., W. W. Schroeder, S. L. Goodrick, J. R. Christy, and A. M. J. Davis, 1995: On the Relationship Between the Katabatic Wind System of the Antarctic and Biological Productivity of the Southern Ocean. To be submitted to *Science*. 1995.

Students: Scott Goodrick, Ph.D. (50%), and David England, Post-Doctoral (65%).

Water-Use of Managed Southern Pine and Natural Hardwood Forests: Scaling Ground-Based Measurements to the Ecosystem Level

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Objectives: In order to evaluate responses of forests to projected global environmental changes, most studies quantify the reaction of individual plants or plant organs (e.g., leaves) to either changes artificially imposed on environmental variables, or to environmental variation to which plants are steadily exposed. Such responses define a point response in a forest. Scaling point measurements to the forest necessitates estimation of the variance, propagated throughout the scaling operation. Here we report on the phase of the project in which the major objective was to estimate stand transpiration by combining single tree information with stand level information and to provide an estimate of the variability in transpiration (E) expected amongst patches in the forest.

One environmental change hypothesized to affect leaf conductance and, thus, stand E is the projected increase in atmospheric concentration of CO₂ (Ca). Based on preliminary results from

the previous phase, we posed the hypothesis that trees in our forests will respond in terms of water relations to elevated atmospheric CO₂ only when soil moisture is ample and the atmospheric vapor pressure deficit (VPD) is low. Otherwise, stomata closure will occur due to moisture stress independent of Ca. Although a large proportion of annual precipitation in this region is deposited during the growing season, the combination of clay soils and relatively restricted root systems due to a shallow clay hard pan results in a rapid depletion of available moisture and development of moisture stress. Thus, the second objective of this study was to identify conditions in which pine trees may close stomata (transpire less at a given VPD) in response to elevated Ca.

Products: (1) A detailed understanding of some water relation processes affecting E and canopy conductance (gc) in pine and hardwood forests. (2) Assessment of the differences among species' responses to VPD and soil

drought. (3) Estimation of the effect of elevated Ca on gc and E of a 12-meter-tall pine stand. (4) A combined empirical and mechanistic model to predict gc and E based on input variables obtained from a National Weather Service Station.

Approach: Variables are measured to estimate E and, using Fick's law of diffusion, to derive gc. Plant variables include leaf area index (LAI), hydroactive xylem area (Sa) of all trees in the stand, and heat flux density (HFD) in the xylem of 10-20 trees representing the species and stature in the stand. HFD can be converted into water flux per unit of Sa and weighted by the Sa of the measured tree, or the sapwood area of all trees of similar species and stature, to give E per tree or stand, respectively. Soil water content was measured using time domain reflectometry and throughfall precipitation was measured under the canopy.

The effect of enriched Ca is evaluated by comparing E and conductance of trees in a *Pinus taeda* L. (loblolly pine) stand within the zone of Ca controlled at 550 Pa by a prototype of the Free Air CO₂ Exchange (FACE) apparatus to trees in the same stand exposed to ambient Ca. Other species which comprise a minor component in the stand include *Liquidambar styraciflua* L. (sweetgum). The diurnal pattern of evapotranspiration from the FACE stand under ambient Ca was also measured using a triaxial sonic anemometer and a krypton hygrometer. The values generated with this eddy correlation method were used as a check on our scaling E from tree to stand.

Results to Date: We presented in the previous SERC-NIGEC meeting preliminary results from FACE prototype built at the Duke Forest. Our earlier measurements demonstrated that despite frequent precipitation events during the southeastern growing season, pines developed water stress quickly between precipitation events, and closed stomata in days of high vapor pressure deficit, even if the soil is nearly saturated. These observations, combined with the preliminary results from FACE, led us to hypothesize that, under unsaturated soil conditions, elevating Ca in FACE will not reduce canopy conductance significantly relative to a reference stand because the trees in both stands would already have low conductance due to moisture stress. We further hypothesized that elevated Ca will result in lower canopy

conductance relative to the reference if moisture stress will be alleviated. Our results from a short term atmospheric CO₂ enrichment and irrigation experiment support these hypotheses. Standardized E of trees in the FACE stand was similar to trees in the reference stand before Ca was elevated (Figure 1); when Ca was elevated, the FACE trees transpired slightly but insignificantly less than reference trees. However, a 13% lower E was measured in FACE trees as compared to reference trees after water was added to both.

We also investigated several scaling issues designed to allow us to estimate forest level water-use from measurements made at different scales, and provide a variance estimate as well. We quantified the variability in each measured variable which is used in calculating forest E. We thus quantified xylem flux density in two zones of the hydroactive xylem (outer 20 mm, and the next 20 mm into the xylem). We found that in ring porous and diffuse porous hardwoods there were no differences in the rate of water flow in the inner and outer xylem, but that in pines the inner xylem conducted water at a rate 0.25 that of the outer xylem, and that the ratio decreased with soil moisture (Figure 2). Not accounting for this small scale variability in flow would have caused 0.5 mm d⁻¹, or up to 30% over estimation of stand E (Figure 3). Other sources of variability in stand E are the result of variability in the flow rate of water per unit of xylem area among neighboring trees, which is partially related to the variability of xylem area per unit of ground area, and the variability in the latter variable (Figure 4). Variability among stands within a forest must also be accounted for when values are scaled to the ecosystem level. For that purpose, we quantified each source of variation and calculated a combined variance. We evaluated how well water flux estimates from branch measurements, scaled to E per unit of ground area agree with whole tree measurements scaled similarly, and estimates from both measurements to estimates from eddy correlation and soil measurements, the latter two representing a larger patch in the stand (Figure 5). At high temporal resolution, soil and whole tree measurements show a comparable trend (Figure 5c), and branch and eddy correlation measurements appear comparable (Figure 5a). For daily sums of E, the estimates based on soil, stem, branch, and atmospheric measurements were within 10% (see Figure 5b for comparison between scaled stem measurements and eddy

correlation). Depending on the temporal resolution necessary to achieve a particular objective, a low data-take rate on stems can estimate well the daily stand E, while a high data-take rate on branches can estimate fairly well diurnal trends in stand E. Because xylem heat flux measurements with the Granier-type sensors are inexpensive and simple to perform, this method represents an attractive approach to estimate latent heat flux from forested ecosystems at different temporal resolutions.

Student participation: Cheng-I Hsieh 10%; Jenny Swanson 20%; Philip Todd 30%; Nathan Phillips 100%.

Manuscripts in preparation and submitted:

Leaf and canopy responses to elevated CO₂ in a pine forest under free-air CO₂ enrichment, accepted for publication in *Oecologia*, April 1995.

A Lagrangian dispersion model for predicting CO₂ sources, sinks, and fluxes in a uniform loblolly pine stand, submitted to *Journal of Geophysical Research*, March, 1995.

Radial trends in xylem flow in non-, diffuse- and ring-porous species, and their effect on calculations of stand transpiration, submitted to *Plant, Cell and Environment*, June, 1995.

Presentations:

Scaling radial sap flow measurements in loblolly pine to stand level. Conference of the American Geophysical Union, Special Session on Scaling Land-surface Processes from Leaf to Canopy, Baltimore, MD, May 30, 1995.

Radial trends in xylem flux density in loblolly pine, sweetgum and white oak. Ecological Society of America Conference, Snowbird, Utah, August 2, 1995.

Other products:

Scaling and modeling transpiration based on water flux measurements at the stem, branch and leaf; by Nathan Phillips. M.S. Thesis, Duke University (expected completion by September, 1995). Water budget and estimation of transpiration based on atmospheric and soil measurements; by Philip Todd. M.S. Thesis, Duke University (expected completion by September, 1995).

Figure 5. Diurnal trends in latent heat flux estimated from sap flux Granier-type sensors in stems and branches, from eddy correlation measurements, and from hydrologic budget using precipitation, drainage calculations and changes in soil moisture.

Figure 1. Transpiration of trees in the Free-air CO₂ Enrichment (FACE) prototype relative to transpiration of trees in a reference stand during a calibration period, a period of elevated CO₂ in FACE, and a period of elevated CO₂ in FACE and irrigation in both stands.

Figure 2. The ratio of water flux in bands (20mm) of inner xylem (20-40mm from the cambium) to outer xylem (0-20mm) during a soil drying period.

Figure 3. Stand-level transpiration estimated based on the assumption that the hydroactive xylem (sapwood) has a uniform water flux rate similar to the outer xylem band, and corrected for the lower flux rate in inner xylem.

Figure 4. Relationship between individual tree daily sums of water flux and stand level sapwood area per unit of ground immediately surrounding each tree.

Enhancement of a Global Soil Pedon Database For Global Change Studies

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Objectives: Process models and methods of analysis for use in integrated assessments and impact analyses of global change require information about soils. These global change studies require soil information for various applications including impacts on terrestrial vegetation dynamics, carbon cycle dynamics, trace gas exchange, and the interactions among these processes.

The most widely used soil data sets are the meter-depth summary of the UCB-ORNL soil profile database and the digitized FAO-UNESCO Soil Map of the World. The UCB-ORNL summary series (Post et al., 1982, Zinke et al., 1984, Post et al., 1985), reports carbon and nitrogen content standardized to 1m depth, interpreted lifezone and ecosystem, location, elevation, and general environmental characteristics for over 4100 globally distributed soil profiles. Soil type and soil texture are not identified in the profiles in this database. The FAO-UNESCO data set provides global geographic distribution of soil type (FAO classification), soil texture, and slope. Other features, such as drainage, are sometimes included.

Static analyses and dynamic process modelling make increasing demands of these data. The value of these data sets to many global analyses would be enhanced if the UCB-ORNL resource was linked to geographic datasets such as the FAO-UNESCO and others by the addition of FAO soil classification designations, soil texture and vegetation cover. Completion of this project will contribute substantially to the IGBP-DIS/GCTE Global Soils Database Project.

Products: (1) Compilation of soil designations for each profile in the UCB-ORNL database. These include FAO-UNESCO soil taxonomic descriptions and USDA-SCS taxonomic descriptions. (2) Compilation of additional information associated with each profile when available from the source material including aspect, vegetation, nutrients in addition to

nitrogen, base cation content, water holding parameters, and climate information. (3) Information summarized to 30cm depth in addition to the 100cm depth. (4) Expansion of the data base with the addition of 200 tropical soil profiles. (5) Conversion of the original data files to a modern database management system format.

Approach: A workshop will define and evaluate the source materials and original data files and determine the nature and scope of specific objectives that can be completed. The UCB-ORNL original data files will be converted into a modern database management program format and initial reports containing all coded data will be prepared and divided among the collaborators. Each collaborator will work with the original source material and add the data enhancements that are possible to the initial report forms. The completed reports will be collected and the new information added to the database. A second workshop will evaluate and finalize the completed database. Documentation and publications using the enhanced database will be prepared for public dissemination.

Results to Date: Our first workshop, a planning/training session in which the data enhancements were planned and coordinated between project participants has been completed. Methods of coding vegetation, soil texture, additional nutrient elements, and other information were developed. All source materials were located and photocopied if necessary and preliminary assignments made to collaborators.

Original UCB-ORNL project data files were reconstructed and a FOXPRO database management file that contains several enhancements to the original, publicly available file has been completed. This file identifies carbon and nitrogen concentrations to 30 cm depth as well as 1 meter for each of the over 4,000 profiles. In addition, information on phosphorus and base cations are reported when available. Any additional site information that

was recorded in these original files was also retrieved and converted to standard formats for incorporation into the database management file. Individual profile reports containing all coded information for each profile have been printed.

Currently collaborators are working on adding soil taxonomic and vegetation information to the initial report forms for each profile in the database. Approximately 2000 profiles have had

USDA-SCS taxonomic names assigned. The remainder will be completed by October 1995.

A second workshop in the fall of 1995 will evaluate and finalize the completed work. This will be followed by documentation and depositing the data set with appropriate dissemination centers and preparation of a manuscript for journal publication that explores the significance of the completed work.

Response of Longleaf Pine to Elevated Atmospheric CO₂: Resource Availability, Carbon Partitioning, and Respiration

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Jeffrey S. Amthor
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Objective: To determine the response of longleaf pine seedlings to CO₂ enrichment, particularly in regard to carbon allocation patterns, construction and maintenance costs, respiration, and root function; and to determine how these responses will be influenced by resource availability and plant phenology.

Product: A detailed, state-of-the-art contribution to the understanding of the effects of elevated CO₂ and interactions with resource availability on plant respiration and on the fate of extra carbon within the plant/soil system for a forest ecosystem species important to the Southeastern United States.

Approach: Longleaf pine seedlings, potted in 45 L plastic pots containing construction grade sand, were exposed to ambient (360 μ mol CO₂ mol⁻¹) or elevated (720 μ mol CO₂ mol⁻¹) CO₂ within open top chambers. Carbon dioxide exposures were initiated on March 30, 1993 and continued, 24 hours day⁻¹, for 20 months. Nitrogen treatments (400 or 40 kg N ha⁻¹ yr⁻¹) were initiated at the time seedlings were planted. Water stress treatments (-0.5 or -1.5 MPa) were initiated following the first harvest and were continued through to the final harvest. In addition to the three harvests reported on

previously, a fourth harvest was conducted at the time of final bud set in the second growing season (November 1994). Biomass, mycorrhizal colonization of fine roots, carbon partitioning, carbon flux, carbon construction costs, and carbon maintenance costs have been determined at each harvest. Carbon maintenance costs have also been calculated from respiration measurements taken periodically during the period of needle expansion (i.e., between the first and third harvests).

Results to Date: Significant positive effects of higher levels of CO₂, N, and H₂O and significant CO₂ x N interactions (positive effects of elevated CO₂ occurred only under high N fertility) on biomass accumulation continued to be observed at the final harvest (Figure 1); however, CO₂ x H₂O interactions were generally not detected. These data support our suggestion that N, but not water, modifies CO₂ response. This may be due to elevated CO₂ affecting water use efficiency to a greater extent than its influence on nitrogen use efficiency. Plants growing under higher levels of CO₂ allocated a greater proportion of their biomass belowground; N and water treatments demonstrated diametrically opposed effects on biomass partitioning (high N reduced partitioning belowground while adequate

water increased root to shoot ratio). The effects of elevated CO_2 on partitioning of biomass belowground were apparent in both N treatments; however, this effect of elevated CO_2 was observed only for plants under water stress (Figure 2), suggesting that elevated CO_2 may ameliorate the negative effects of water stress.

Numbers of ectomycorrhizal short roots per centimeter of fine root were quantified and percentage of mycorrhizal short roots was calculated from fine roots collected at the final harvest. Elevated CO_2 continued to demonstrate increased number of ectomycorrhizae and percentage of mycorrhizal short roots, but the increase was not significant for the number of ectomycorrhizae per unit length of fine root. Numbers of ectomycorrhizae and percentage of mycorrhizal short roots were decreased by the high N treatment and by water stress. There continued to be few significant interactions among the main treatment variables. Elevated CO_2 resulted in a large increase in the total number of ectomycorrhizae per seedling, but the percent increase compared to ambient CO_2 declined from 100% at the first two harvests to 44% at the final harvest.

We reported previously that apparent respiration rates of longleaf pine foliage was significantly increased under elevated atmospheric CO_2 when expressed per unit foliar N, but was not effected by CO_2 when expressed on a leaf area or leaf dry weight basis; nitrogen strongly affected apparent respiration rates, but no $\text{N} \times \text{CO}_2$ effects were detected. Additional respiration measurements comparing the effects of CO_2 , N, and water stress on first-year foliage, fully developed under CO_2 and resource treatments, with newly initiated needles have been completed. Photosynthetic rate of these plants was also assessed the day prior to respiration measurements to determine if these two physiological responses are correlated. Elevated CO_2 decreased cost of construction (i.e., growth respiration) of pine foliage, while increased N resulted in greater construction costs; however, the magnitude of the CO_2 effect was relatively small (2.6% in high N and 0.6% in low N). High levels of N fertility tended to increase the concentration of sugars belowground and to decrease the concentration of starches in all tissues, except fine roots. The concentration of starches in all longleaf pine tissues was significantly increased by elevated CO_2 ; however, the concentration of sugars was higher only in

fine roots. No $\text{CO}_2 \times \text{N}$ interactions were observed for any carbohydrate in any pine tissues.

These results demonstrate that elevated CO_2 influences physiological processes such as biomass production and partitioning, colonization of fine roots by ectomycorrhizal fungi, and plant respiration. They further show that plant responses to a higher CO_2 atmosphere are modified by availability of vital resources. Evidence suggests the way in which environmental stresses influence plant responses to CO_2 may differ; nitrogen availability appears to moderate the response of longleaf pine to elevated CO_2 , whereas elevated CO_2 appears to moderate the response of these plants to water stress.

A number of plant species (southern red oak, chestnut oak, live oak, longleaf pine, loblolly pine, sour orange, wiregrass, and curly dock) are being grown in the Duke University Phytotron at two levels of CO_2 and two levels of nitrogen fertility. Respiration rates of these plants will be measured after 60 and 120 days exposure to the CO_2 and N treatments in order to determine the extent to which variability in respiratory responses to elevated CO_2 are due to ecophysiological differences among species and the extent to which they are due to differences in growth conditions and measurement techniques. Photosynthetic rate of these plants will be measured the day prior to night respiration measurements. This will provide a measure of the extent to which photosynthesis regulates respiratory response to CO_2 .

Presentations:

Rogers, H.H., Mitchell, R.J., Runion, G.B. and Wood, C.W. 1993. Response of longleaf pine to elevated atmospheric CO_2 : Resource availability, carbon partitioning, and respiration. NIGEC Symposium on Global Change Research: Reducing Scientific Uncertainty. Tuscaloosa, AL. April 28-29, 1993. (Abstract).

Mitchell, R.J., Runion, G.B., Rogers, H., Prior, S. and Amthor, J. 1994. Response of Longleaf Pine to Elevated CO_2 : Effects of Multiple Resource Limitations on Growth, Carbon Partitioning and Respiration. Oak Ridge Conference on Global Environmental Change. Oak Ridge, TN. March 28-30, 1994. (Abstract).

Mitchell, R.J., Runion, G.B., Rogers, H., Prior, S. and Amthor, J. 1994. Response of Longleaf Pine to Elevated CO₂: Effects of Multiple Resource Limitations on Growth, Carbon Partitioning and Respiration. First Annual Alabama EPSCoR Colloquium. Tuscaloosa, AL. April 26, 1994. (Abstract).

Mitchell, R.J., Runion, G.B., Prior, S.A., Amthor, J.S. and Rogers, H.H. 1994. Respiratory Responses of Longleaf Pine to Elevated CO₂: Effects of Nitrogen Limitations. Ecological Society of America Annual Meeting, Knoxville, TN, August 7-12. (Abstract and Poster).

Mitchell, R.J., Runion, G.B., Prior, S.A., Amthor, J.S. and Rogers, H.H. 1994. Respiratory Responses of Longleaf Pine to Elevated CO₂: Effects of Nitrogen Limitations. ECOCRAFT International Symposium on Responses of Trees and Forests to Global Change. Dourdan, France. October 19-22. (Abstract and Poster).

Runion, G.B., Mitchell, R.J., Rogers, H.H. and Prior, S.A. 1994. Effects of Resource Limitations and Elevated Atmospheric CO₂ on Ectomycorrhizae of Longleaf Pine. American Phytopathological Society Annual Meeting, Albuquerque, NM. August 6-10. (Abstract).

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Publications:

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Prior, S.A., Runion, G.B., Mitchell, R.J., Rogers, H.H., and Amthor, J.S. 1995. Effects of atmospheric CO₂ on *Pinus palustris*: Nitrogen and water limitations on carbon production and allocation. (In preparation for submission to *Plant, Cell & Environment*; projected submission date August, 1995).

Students: (All are Undergraduate Assistants), Trina Cagle (50%), Barry Dorman (15%), Philip Cleveland (20%), John Nance (75%), Evan Sullivan (75%), Tiffanie Starr (100%) (summer).

Figure 1. Total above- and belowground longleaf pine biomass from the final harvest as affected by nitrogen and atmospheric CO₂.

Figure 2. Root to shoot ratio for longleaf pine from the final harvest as affected by water stress and atmospheric CO₂.

Cloud-Climate Feedback Mechanisms: Impact of Reduction in Fossil-Fuel Emissions

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North Carolina State University

P.A. Durkee
Naval Postgraduate School

Objectives: The purpose of this project is to present tangible evidence of the impact of sulfate aerosols on the cloud chemistry and albedo based on observations recorded at a land-based, mountain top location in the Mount Mitchell (35°45'05" N, 82°17'15" W, 2038 m or 6,684 ft MSL elevation—the highest peak east of the Mississippi River) State Park which is designated as a United Nations Biosphere Reserve in western North Carolina. Simultaneous in situ and satellite measurements are analyzed to detect the "fingerprints" of anthropogenic influences on cloud albedo over a dark land surface provided by a montane red spruce/Fraser fir ecosystem.

Products: During the second field season (15 May - 15 Aug 1994), we have produced 343 case studies of clouds formed in air masses of varying degree of the pollution content. We have compiled case studies relating: 1) the activation spectrum of cloud condensation nuclei (CCN) in the cloud forming air masses to cloud droplet size distribution; 2) the cloud water acidity to the cloud albedo; 3) the effective cloud droplet radius and number concentration to the cloud albedo; and 4) the cloud albedo determined from in situ microphysical measurements to the one determined from the AVHRR data.

Approach: Cloud water samples were taken at the experimental site (2006 m ASL) on Mt. Gibbs, which is 3.3 km southwest of Mount Mitchell, during 1994 field season. The 1994 data was the result of a continuous field campaign through the months of May through August. Lin and Saxena (1991) give a description of the guidelines used for the onset and termination of cloud events. Ambient meteorological data were obtained by instruments located on the main observational platform, a 16.5 m walk-up tower. The Atmospheric Sciences Research Center (ASRC) passive cloud water collector (DeFelice and Saxena, 1992) was deployed on the tower's

vertically movable carriage, for collecting cloud water droplets during cloud events. Clouds, transported by the ambient winds, would deposit the droplets upon strings on the collector. Cloud water samples underwent a preliminary analysis which consisted of a check of the pH with a standard pH probe and weighing of the sample. The sample was then sealed and refrigerated for further analysis of ionic composition and a quality control check of the pH. A Forward Scattering Spectrometer Probe (FSSP) was deployed upon the same vertically movable carriage as the ASRC cloud water collector. This device was used to obtain number counts and size distributions of cloud droplets during cloud events, such that calculations of effective radius, cloud droplet number concentration (N_d) and liquid water content (LWC) were obtained from the measurements. The CCN activation spectra were measured by a Horizontal Thermal Gradient Cloud Condensation Nucleus Spectrometer described by Fukuta and Saxena (1979a,b). The CCN activity spectra were measured at the beginning of every hour in pre-cloud air masses. Measured activity spectra were recorded manually or automatically with an x-y recorder. Activation spectra measured in the hour previous to the cloud event were assumed to be representative of the cloud forming air mass. The sampling arrangement was such that the CCN spectrometer sampling was done at the same level as the FSSP probe. Backward air parcel trajectories (back trajectories) were run for each cloud event. Nested Grid Model (NGM) data were used for three-dimensional boundary-layer trajectory runs. The Hybrid Single Particle Lagrangian Integrated Trajectory (HY-SPLIT) model (Draxler, 1992) was used for back-trajectory calculation as well as to compute representative soundings over the Mt. Mitchell site where the cloud depth H was estimated. By calculating cloud depth H from soundings, knowing CDNC and τ , the optical depth of cloud (τ) is calculated as follows (Twomey, 1977),

(1)

where ρ is the density of liquid water (1000 kg m⁻³). The albedo (A) may be evaluated using the relationship (Lacis and Hansen, 1974)

(2)

Equations (1) and (2) were used to calculate in situ albedo for cloud events occurring at Mt. Mitchell. Remotely sensed albedos were measured using the Advanced Very High Resolution Radiometer (AVHRR) aboard NOAA-11 and NOAA-12 polar orbiting satellites. Since the drop sizes are sufficiently large compared to the wavelength of Channel 1 (0.54 to 0.80 μm centered on 0.65 μm), the optical thickness is almost independent of wavelength. Therefore we use the monochromatic optical thickness at 0.65 μm as the principal parameter to calculate cloud radiative properties such as albedo. Figure 1 shows the categorization of air masses traversing the Mount Mitchell observation site adopted by utilizing anthropogenic emissions of SO_x provided by the Environmental Protection Agency (EPA, 1993). The system characterizes air masses as "polluted" if they are transported from a region bounded by 290° to 65° (Sector 1) azimuth relative to Mount Mitchell, "marine" if transported from a region bounded by 240° to 65° (Sector 2) and "continental" if transported from a region bounded by 240° to 290° (Sector 3).

Results to Date: Table 1 gives the number of events for each year and month as well as total time, by event category, of all events observed within each individual month of sampling for the combined years (1993-95). Air masses which were found via HY-SPLIT to be of polluted origin were correlated with the lowest mean pH values. Marine sector air masses (singly and in combinations) resulted in cloud water pH values lower than those observed during previous years. Continental air masses, and air masses containing either primary or secondary continental influence yielded mixed results. Exclusively continental air masses were most commonly observed air masses from the field season and also were correlated with some of the highest pH observations and corresponding low values of acidifying ion concentrations. Elevated levels of cloud water acidity for cases coincident with continental sector influence can be attributed to a combination of low pollutant aerosol emissions from Sector 3, as well as from the neutralizing impact of medium-to-high levels of alkaline soil aerosol particles such as calcium and magnesium ions. Nagamoto et al. (1983) have shown that soil-based aerosols produced by wind erosion can result in the neutralization of cloud water near Denver, Colorado. Land-

crossed air mass categories display high average concentrations of alkaline cations, and the net increase in cloud water acidity may have been enhanced due to these aerosols.

Table 1. Summary of Cloud Episodes

	1993	1994	1995*
Total Events	39	60	15
Total Duration (hrs.)	159	373	112
Avg. Duration (hrs.)	4.1	6.2	7.5
Minimum pH	2.6	2.3	3.0
Samples Analyzed	234	710	45

*As of June 16, 1995.

Correlation between sulfate and hydrogen ion concentrations for field, laboratory and calculated values based on electroneutrality showed that the sulfate continued to be the primary contributor to the acidity of cloud and rain water at Mount Mitchell, with nitrate, ammonium and hydrogen ions essentially controlling the observed acidity levels. Since the sulfate and nitrate were the ions mainly responsible for reducing cloud water pH values, and since these ions were found to have their highest average concentrations associated with polluted sector air masses, we have demonstrated that air masses originating from, or passing through the urban-industrial regions of the U.S. can impact the chemical, microphysical, and optical properties of clouds at remote, rural locations (see Figures 3 and 4). Because these aerosols (both natural and anthropogenic) can be very efficient CCN (see Figure 2), extrapolation of our observations would indicate that anthropogenic emission of the precursor aerosols and gases of sulfate and nitrate from all areas can affect the regional climate. It is thus of considerable importance to continue the monitoring of not only the emission patterns of these pollutants, but also the physico-chemical effects of these pollutants as well.

Student Participation: John Anderson 25%; Brian Logie 50%; Brian Wenny 50%; Shannon Schafer 25%; Catherine Deininger 25%.

Publications:

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Lin, N.-H. and V.K. Saxena, 1991: In-cloud scavenging and deposition of sulfates and nitrates: Case studies and parameterization. *Atmos. Environ.*, 25A, 2301-2320.

Nagamoto, C.T., F. Parungo, R. Reinking, R. Pueschel and T. Gerish, 1983: Acid clouds and precipitation in eastern Colorado. *Atmos. Environ.*, 17, 1073-1082.

Twomey, S., 1977: *Atmospheric Aerosols*. Elsevier, Amsterdam.

Presentations: 9 presentations were given between 6/94 and 6/95.

Theses: Kerry L. Burns M.S., James C. Ulman M.S.

Figure 1. The 1991 U.S. EPA Emissions Inventory of anthropogenic sulfur oxides (SO_x) for the eastern United States.

Figure 2. a) CCN concentration in pre-cloud air vs. resultant cloud water pH, b) CCN concentration vs. cloud droplet concentration, and c) CCN supersaturation vs. CCN concentration.

The Effects of Rainfall Modification on Plant-Herbivore Processes

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Objectives: This study is part of a long-term experiment at the Oak Ridge National Laboratory which is examining the impact of climate-induced rainfall modification on eastern deciduous forests. Our particular project is evaluating the changes in plant resource allocation to foliar nutrients and phenolic defenses following rainfall manipulation and quantifying the extent of insect herbivory from tree species experiencing wet, ambient or drought conditions.

Products: The project provides an opportunity to extend climate change research by addressing the consequences of rainfall modification on consumer-related processes. We expect to develop an understanding of how plant allocation patterns to foliar nutrients and chemical defenses are altered under wet or drought conditions and the consequences of any changes in allocation patterns on plant susceptibility to insect herbivores. We will determine which stage of the life cycle of tree species is most susceptible to herbivore attack while experiencing different moisture regimes and thereby assess the role of changes in plant defense allocation and insect herbivory on plant mortality and regeneration capacity.

Approach: The experiment was initiated on the Walker Branch Watershed at ORNL in July 1993 and is using a gravity driven transfer of 30% of total throughfall precipitation to create dry, ambient and wet plots (0.64 ha each) within the watershed. We are using seedlings, saplings and mature trees of white oak (*Quercus alba*), chestnut oak (*Q. prinus*) and red maple (*Acer rubrum*) to satisfy our objectives. Twenty seven trees of each species were selected from within each 0.64 ha experimental plot (243 total trees). Extension pole cutters were used to obtain leaves from each tree in late August 1992 and in early July and late August of 1993 and 1994. The leaf samples are photocopied and then processed for chemical analysis. The photocopy of each leaf is digitized to determine total leaf area and the extent of damage by each major insect feeding guild including strip feeders, pit feeders, leaf skeletonizers, leaf miners, leaf galls and leaf rollers.

Leaf chemical analyses include foliar nitrogen, total phenolics, hydrolyzable tannins and condensed tannins. Foliar nitrogen determinations are being conducted through the Plant Analysis Laboratory at the University of Georgia. Total phenolic content is assayed using the Folin-Denis technique, while condensed and hydrolyzable tannin assays are performed according to Bate-Smith procedures.

Results to Date: The early treatment results indicate no real change in plant-herbivore processes between dry, ambient and wet plots. Foliar N concentrations of each species were quite similar in dry, ambient and wet areas during 1994 (Figure 1). Interspecific patterns of plant phenolics have remained unchanged from 1992-1994; oak leaves consistently contained more hydrolyzable tannins whereas maple trees allocated more carbon to condensed tannin production. However, no differences in phenolic concentrations developed between treatment areas in 1994 (Figure 2). The overall absence of treatment differences in 1994 probably reflects the wet summer. Soil moisture reductions on the dry plot were apparently not sufficient to affect plant foliar chemistry during an especially wet year.

Rainfall effects were evident when comparing our results over the three-year period. Leaf nitrogen concentrations in all species were approximately 10% lower in the much drier summer in 1993 than 1992 (Figure 3). Foliar N levels in oaks returned to pre-drought levels during the wet summer of 1994, although N concentrations in maple leaves remained reduced in 1994. Phenolic levels in tree species were also much lower in the drier 1993 than 1992 summers (Figure 4). However, total phenolic and hydrolyzable tannin levels remained low in 1994, whereas condensed tannin production was much higher for all species in the wet summer. These results showed consistent reductions in plant allocation to foliar nutrients and phenolic defenses during drought. In contrast, the degree of recovery of foliar chemistry following drought varied between species and for different categories of phenolics.

Insect herbivore damage was lower on both oak species in 1993 than 1992 despite the reduction in phenolic defenses (Table 1). The reduced feeding from white oak and chestnut oak trees in 1993 may have occurred in response to the poorer nutritive quality of oak leaves during the drier summer. Feeding by leaf skeletonizers was much less in 1993 than 1992 and accounted for nearly all of the reduction in leaf damage on both oak species. In contrast, herbivore damage on red maple trees, which experience very little feeding by skeletonizers, was identical both years. Our results from 1994 indicate that herbivore damage was elevated on all species during the wet summer (Table 1), primarily because of increased consumption by strip feeders (i.e. caterpillars). These results thus suggest that the responses of insect herbivores to rainfall fluctuations may be largely guild specific and appear closely related to changes in foliar nutritive quality. Continuation of the Throughfall Displacement Experiment should enable us to further examine the response of particular insect feeding guilds to moisture-induced changes in plant nutrients and phenolic defenses.

Manuscript in final preparation:

Shure, D.J., P.D. Mooreside and S.M. Ogle. Rainfall effects on plant-herbivore processes in an upland oak forest.

Presentations:

Plant-consumer adjustments to rainfall modification: a climate change experiment. Seminar presented at University of South Carolina. Columbia, SC, November, 1994.

The effects of rainfall modification on plant-herbivore processes. Presented at NIGEC, Oak Ridge Conference on Global Environmental Change. Oak Ridge, TN, March 1994.

The effects of rainfall modification on plant-herbivore processes. Presented at the NIGEC Research Symposium, Reducing Scientific Uncertainty II, Tuscaloosa, AL, April, 1995.

The effects of rainfall modification on plant-herbivore processes. Scheduled for presentation at the annual meeting of the Ecological Society of America. Snowbird, UT, July, 1995.

Student Participation: Kenneth Peavy 5%.

Figure 1. Nitrogen levels (means and 1 SE) in leaves (% dry weight) from different life-cycle stages of tree species sampled in the experimental area in August 1994.

Figure 2. Levels of phenolic chemistry (means and 1 SE) in leaves of different tree species sampled in the experimental area in August 1994. Total phenols are expressed as % tannic acid equivalents (TAE), hydrolyzable tannins as mg of hexahydroxydiphenoylglucose equivalents per g of leaf tissue and condensed tannins as % Quebracho tannin equivalents (QTE).

Figure 3. Nitrogen content in leaves (% dry weight) of different tree species sampled in the study area in August 1992 and July and August of 1993 and 1994. Means represent all trees sampled for each species.

Figure 4. Levels of phenolic chemistry in leaves of different tree species sampled in the experimental area in August of 1992, 1993 and 1994. Total phenols are expressed as % tannic acid equivalents (TAE), hydrolyzable tannins as mg of hexahydroxydiphenylglucose equivalents per g of leaf tissue and condensed tannins as % Quebracho tannin equivalents (QTE).

Table 1. Percent leaf area damaged (means and 1 SE) by insect herbivores on tree species sampled in the study area over a three-year period. Totals for each year have been averaged over all treatment plots and life cycle stages.

	1992	1993	1994
WHITE OAK			
Strip Feeders	6.85	6.54	8.49
Skeletonizers	4.52	3.11	4.10
Total	12.4 ± 0.59	10.1 ± 0.57	13.1 ± 0.87
CHESTNUT OAK			
Strip Feeders	4.41	4.99	5.51
Skeletonizers	3.66	2.44	5.06
Total	8.6 ± 0.53	7.7 ± 0.59	10.8 ± 0.82
RED MAPLE			
Strip Feeders	4.93	5.38	8.10
Skeletonizers	0.33	0.24	0.26
Total	6.0 ± 0.52	6.0 ± 0.64	8.7 ± 0.75

Implementation of a Regional System for the Diffusion of Global Environmental Change Education Through In-Service Training of Grade School Teachers

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Objectives: According to the National Oceanic and Atmospheric Administration's Office of Global Programs, "NOAA recognizes the importance of education both formal and informal to ensuring that the results of scientific research on global environmental issues like climate change and ozone depletion are effectively applied to individual and societal decision making"¹. If teaching about global environmental change is to improve significantly over the short term, vehicles must be found to enhance educational opportunities for practicing teachers in the grade schools with respect to the application of the results of ongoing global change research. The primary objective of this project is to implement an effective regional system for the diffusion of global environmental change education. A second goal is to make the delivery system efficient (low cost) relative to the benefits achieved through the scope of the diffusion process. The specific region of concern is the southeast United States, and the constituency consists of teachers of both social studies and natural science, grades 4-12.

Products: The essential product is a set of in-service teachers with three kinds of improved capabilities. The first of the enhanced capabilities is improved understanding of themes and concepts in global environmental change. A second is increased knowledge and use of methods and materials for teaching about global environmental change. The third is training necessary to provide effective and stimulating in-service presentations on global change issues to peer groups of teachers.

Approach: The program consisted of a two week summer institute for in-service teachers of social studies, and science (grades 4-12). The institute on "Issues in Global Environmental Change" was planned according to a standard National Geographic Society Alliance Network formula as a two week residential experience involving a mix of content lectures, classroom activity demonstrations, field trips, and resource demonstrations².

The central focus of the institute was the provision of current information via lecture discussion and printed materials on a variety of aspects of global environmental change. Particular emphasis was placed on issues of human interaction with various segments of the environment including the atmosphere, lithosphere, biosphere, and hydrosphere. Major topics included natural climate variability, greenhouse effect, ozone depletion, and ecosystem response. Individual content lectures were provided on a variety of topics including: population and resources; deforestation, desertification, and biological diversity; endangered species and extinction; flooding and other natural hazards; past environment reconstruction; climatic change - evidence and theory; enhanced greenhouse effect; El Nino/southern oscillation; relations between climates; and terrestrial biomes and impact of climate change on agriculture. Great effort was made to explain linkages and interdependencies and to identify those areas subject to uncertainty and current scientific debate. The lectures were presented by specialists from the fields of biology, geography, geology, meteorology/climatology, and science education.

Significant effort was made in the institute to provide teachers with ideas for developing study units and classroom activities for particular grade levels. Among the topics covered were desertification, rain forest destruction, endangered species, water supply, water quality, greenhouse effect, population/resource ratios, and computer based teaching strategies.

Results to Date: A requirement for participation in the summer institute was agreement by the teachers to return to their home state and provide further in-service instruction on global change issues. Four follow-up one day in-service programs on environmental change issues were arranged during the past academic year to which institute participants were invited as presenters. These programs were conducted in Tupelo, Mississippi, Decatur, Alabama, Augusta, Georgia and Columbia, South Carolina,

with the sites being selected to facilitate travel from adjacent participating states. All of the participating teachers have reported completing at least one in-service training activity with several teachers reporting multiple presentations. The participants themselves rated the institute highly in their program evaluation. Their primary recommendations were to increase the amount of field experiences if possible and to allow for more follow-up sessions to the main program. Their recommendations have been taken into account for the proposed second year of the institute program in the summer of 1995.

References:

Mortenson, Lyn L. (Ed) Global Change Education Resource Guide, University Corporation for Atmospheric Research, 1994.

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Increasing Accuracy of Climate Change Models by Application of Lipid Molecular Techniques to Assess Belowground Biomass, Prokaryotic and Eukaryotic Community Shifts, and Nutritional/Physiological Status (for estimating mineralization activity) in the Rhizosphere and Soils of Important Southeastern US Plants Exposed to Elevated CO₂

David C. White

The University of Tennessee, Knoxville

Objectives: The hypothesis states that exposure of plants to elevated atmospheric CO₂ will induce an increase in belowground carbon stores. These exposures will result in an increase in the viable and non-viable rhizosphere associated microbial biomass. Objectives of this research are to quantitatively define, by use of the signature lipid biomarker technique (SLB), the increases in microbial biomass and any shifts in microbial community composition that may also occur. Since the SLB analyses can also provide insight into the physiological or metabolic status of a microbial community, mineralization rates of the belowground carbon stores will be inferred.

Products: (1) An assessment of the impact elevated atmospheric CO₂ has on microbial biomass, community composition and physiological status when associated with different species of plants (long needle pine, white oak, sugar maple, C₃ and C₄ grasses) collected from different geographical locales (Southeastern and Midwestern US and central Europe). (2) Estimations of belowground carbon mineralization rates under ambient and elevated atmospheric CO₂ levels by quantifying changes

in membrane lipid patterns. (3) A phenotypic description (membrane lipid) of a number of fungal root colonizers for use in taxonomic relationships and in the identification of lipid biomarkers for *in situ* identifications.

Approach: Membrane lipids are used in determining the prokaryotic and eukaryotic biomass, community composition, and metabolic status. This approach eliminates the bias of classical isolation and culture techniques and allows for an application to a wide variety of environmental samples. This study focuses on the rhizosphere associated microbiota requiring that both fine root and surrounding soils be analyzed. Ester-linked phospholipid fatty acids (PLFA) provide insight into community composition and can be recovered quantitatively thereby providing an accurate measure of the viable biomass. Inherent differences in PLFA structure, resulting from differences in biosynthetic pathways, allow for the independent interpretation of prokaryotic and eukaryotic communities. The analysis of sterols provides additional insight into eukaryotic composition, specifically mycorrhizal. Prokaryotic physiological status is estimated from ratios of

specific PLFA. Due to the quantitative nature of the assay the ratios, when used in conjunction with other activity measures, can be used to determine carbon mineralization rates.

Results to Date: Application of a neural network to the PLFA profiles obtained from white oak rhizospheres demonstrated that identifiable differences in community compositions occurred under ambient and elevated atmospheric CO₂ levels. The neural network was applied after other statistical tests, such as ANOVA or multivariate, showed little significance between PLFA molar percentages under the two CO₂ levels. Analysis of litter material from the same white oaks showed prokaryotic biomass to be greater than that observed in the rhizosphere (Table 1) and that the prokaryotic community composition was enriched in PLFA indicative of gram negative bacteria (Figure 1).

Analysis of rhizosphere community responses to elevated atmospheric CO₂ in association with nitrogen additions and water stress showed little significance due to elevated CO₂ but considerable significance due to both water stress and nitrogen additions (Figure 2). In summary: 1) different stages in the pines growth cycle yielded different prokaryotic communities with PLFA indicative of gram negative bacterial populations decreasing from mid-season to bud-set, 2) during bud-set water stress was the primary variable influencing prokaryotic community composition whereas nitrogen superseded water in influencing composition during bud-break, 3) during mid-season and with no water stress, nitrogen addition resulted in an increase in prokaryotic biomass and a shift in community composition towards one representative of soil actinomycetes. Preliminary results indicate that significant shifts in prokaryotic biomass and community composition resulted from elevated CO₂ exposures when associated with the greater nitrogen additions.

The recovery of both PLFA and sterols from sixteen species of fungal root colonizers allowed for a taxonomic comparison to be made which showed that relationships based on the lipid profiles accurately related the organisms at the class level (Figure 3). In addition, penetration of fungal hyphae into a sterile soil were detectable by application of the PLFA analysis. Significant increases in the molar percentages of PLFA indicative of fungi were observed.

In addition to the above, preliminary results have been obtained from a second harvest of white oak litter and from the initial rhizospheres of sugar maples exposed to elevated CO₂ levels. Collaborations have also been established for the procurement of C₃ and C₄ grasses for rhizosphere analyses and for pure cultures of ecto-mycorrhizal isolates.

Students: Amy L. Spann and Julia O. Stair, both are pre-masters students at the University of Tennessee, Knoxville.

Publications:

Ringelberg, D.B., J.O. Stair, R.J. Norby, E.G. O'Neill, D.R. Zak, and D.C. White. 1995. Elevated atmospheric CO₂ and the below-ground microbiota of *Quercus alba* L. *Global Change Biology*, Submitted.

		nmol PLFA/gram	
		rhizosphere	litter
prokaryotic	<0 μ methyl	135 (32)	401 (131)
	+150 μ methyl	100 (34)	330 (50)
	+300 μ methyl	135 (32)	300 (101)
eukaryotic	<0 μ methyl	170 (52)	307 (122)
	+150 μ methyl	119 (37)	260 (54)
	+300 μ methyl	174 (56)	325 (71)

values represent an average with standard deviation in ()
for rhizosphere n=18, for litter n=10
differences between rhizosphere and litter means are significant (Tukey HSD, 95% confidence)

Table 1. A comparison of viable microbial biomass between white oak rhizosphere and litter material expressed as nanomoles of ester-linked phospholipid fatty acids (PLFA) per gram. Prokaryotic PLFA were defined as those of less than 20 carbons in length with no more than one degree of saturation and eukaryotic PLFA as those with more than one degree of unsaturation but also included oleic acid.

Figure 1. Principal components analysis of white oak rhizosphere, non-rhizosphere bulk soil, and litter PLFA molar percentage profiles. The six most positively weighted loadings for each principal component are listed to the right with a description as the type of organism from which they likely originated.

Figure 2. A hierarchical cluster analysis of arcsin transformed ester-linked phospholipid fatty acid (PLFA) molar percent profiles obtained from long needle pine rhizospheres sampled during three points in the growth cycle (mid-season, bud-set, and bud-break), subjected to ambient (L) and elevated (H) levels of CO₂ (360 and 720ppm), nitrogen (40 and 400kg/hr/yr), and the absence or presence of water stress.

Figure 3. Hierarchical cluster analysis of arcsin transformed ester-linked phospholipid fatty acid (PLFA) and sterol molar percent profiles of 16 species of fungal root colonizers. The isolates were analyzed in mycelia form except when indicated as 'Con' for conidia form and 'scler' for sclerotia form.

Western Regional Center

Thomas H. Suchanek, Director

This report covers primarily the time period from July 1994 through June 1995 which, for purposes of reporting, will be considered the academic FY 1994/95. During FY 1994/95 the Western Region of NIGEC included the following states: Alaska, Arizona, California, Idaho, Hawaii, Nevada, Oregon, Utah and Washington, plus the Pacific Territories.

The Western Regional Center (WESTGEC) has experienced many significant changes during FY 1994/95. The most significant have been:

New Site Location for WESTGEC:

The Western Regional Center office for NIGEC, previously co-located with the NIGEC National Office at Research Park, just off the U.C. Davis campus, was moved in July 1994 to the Division of Environmental Studies on the core campus of UC Davis.

New WESTGEC Staff:

New Assistant Director: Dr. Susan Ustin (UC Davis) was approved as the first Assistant Director of WESTGEC. Director Suchanek's background as an ecologist is well complemented by Dr. Ustin's expertise in remote sensing and forest productivity and her long-standing research affiliation with NASA. She has a strong ongoing involvement in research issues relating to global environmental change.

New Administrative Assistant: Barbara Silkbaken (Administrative Assistant for WESTGEC since its inception) made a family-related move to Iowa. Barbara made significant contributions to the WESTGEC program and will be missed. She has been replaced by Linda Ono, who began in July 1994. We welcome her into this new position.

New WESTGEC Representative to the NIGEC Board of Trustees:

Dr. Harold Johnson (UC Berkeley) stepped down as one of the two Western Regional representatives to the NIGEC Board of Trustees. Dr. Don Nielsen (Professor Emeritus at UC Davis) was approved by the NIGEC Board of Trustees and DOE in March 1995 to replace him. We are pleased to have Dr. Nielsen on board. He is a physical scientist who understands both biology and ecology and has taught, conducted research and applied his education and experience toward a better understanding and management of our global resources for thirty-six years. His many awards for his excellent contributions to science, plus his strong background in issues relating to global environmental change, attest to his appropriateness for this position. Currently, the other NIGEC representative is Dr. Malcolm Hughes (U Arizona).

Preparation for FY 1995/96 Projects:

In May 1994 the director conducted a reconnaissance trip throughout the Western Region to promote NIGEC's and WESTGEC's revised agenda, to evaluate the diversity of investigators who are conducting research on global environmental change issues, and to solicit research proposals for FY 1995/96 funds (especially from institutions within states that have been poorly represented in previous years). He made presentations at the University of Utah in Salt Lake City, the University of Nevada at Reno, Arizona State University in Tempe, Oregon State University at Corvallis, the University of Washington in Seattle, the University of California at Los Angeles, and the University of California at Davis.

New Research Directions for WESTGEC in FY 1995/96:

With newly adjusted directives from the Clinton/Gore Administration and a concomitant re-direction from DOE, a major shift in priorities was implemented to increase funding for research on ecological impacts

and human/social issues. These shifts in priorities were incorporated into the RFP for 1995/96 funds (RFP released September 1994) and the resulting project research plan for WESTGEC was forwarded to DOE in February 1995.

Nobel Prize Awarded to the Previous WESTGEC Co-Director Dr. F. Sherwood Rowland: A noteworthy recent event occurred recently that, although it falls outside the reporting period of this Annual Report, deserves mention. Dr. F. Sherwood Rowland, the past Co-Director of WESTGEC, received the prestigious Nobel Prize in Chemistry for his pioneering work on atmospheric gases that have the potential to break down our protective ozone layer. We applaud Dr. Rowland for his excellent contributions to basic science and his visionary research on processes affecting global climate change.

RESEARCH PRIORITIES FOR WESTGEC (FY 1994/95):

Research priorities for ongoing projects during FY 1994/95 projects were:

- Studies of factors that influence atmospheric concentrations of greenhouse gases with emphasis on geochemical studies that help diagnose global processes affecting greenhouse gases.
- Studies of the dynamics and variability of terrestrial hydrological factors which influence global climate change.
- Studies on the dynamics of the coupling of the atmospheric system with the ocean/land system including the role of aerosols and/or clouds, including relevant chemistry modeling or observational approaches which reduce uncertainties about controlling processes.

RESEARCH PRIORITIES FOR WESTGEC (FY 1995/96):

Research priorities for upcoming FY 1995/96 funds (announced in the RFP released in September 1994) were:

- Ecosystem impacts resulting from global climate change.
- Quantitative role of the terrestrial biosphere as a source/sink of CO².
- Human dimensions: economic and/or societal effects of global environmental change.

REQUEST FOR PROPOSALS AND PROPOSAL REVIEW PROCESS: FOR 1995/96 FUNDS

The RFP for upcoming FY 1995/96 funds was released September 1, 1994 with pre-proposals (Letters of Intent) due October 5th and full proposals due November 15th. WESTGEC received 130 pre-proposals and after reviewing each proposed project, communicating with the investigators, and encouraging several projects that might fit into a well integrated package, we received a final count of 60 full proposals. Each proposal was sent out for peer review to 3-5 individuals. We held a Panel Review Meeting on January 12, 1995 at U.C. Davis with the following participants: T. Suchanek (UCD), S. Ustin (UCD), M. Ghil (UCLA), W. Reeburgh (UCI), M. Hughes (UAZ), R. Norgaard (UCB), R. Waring (OSU), L. Ono (WESTGEC Administrative Assistant, UCD).

In addition to mail reviews, each proposal is reviewed by the NIGEC National Program Office, the National Technical Advisory Committee (NTAC) and DOE. DOE performs its own "Relevancy Review" to evaluate how appropriate each project is to their mission statement and programmatic agenda. In the final analysis, proposals for each funding year are typically grouped into three categories: GROUP I proposals are those which received the highest rated reviews and which best fit into the WESTGEC regional plan. GROUP

II proposals are those proposals which received high quality reviews (but not as highly ranked as those in Group I) and which could be funded, given sufficient available funding. This second category might come into play, for example, if a GROUP I proposal were eliminated by DOE as being "non-relevant". GROUP III proposals are those that are not recommended for funding, typically due to poor reviews and/or non-relevancy to NIGEC or WESTGEC priorities.

With input from the mail reviews and the panel review meeting, we recommended 21 GROUP I proposals, five of which were renewals, and two of which we requested funding assistance from the NIGEC National Program Office. We also recommended an additional 11 proposals in GROUP II, to be funded if additional funds became available.

On April 4th the six Regional Directors met at U.C. Davis to discuss integration of research programs between the regions and on April 5th and 6th, all of the directors met with DOE, NIGEC and NTAC to discuss program development and funding for FY 1995/96 projects.

WESTGEC's recommended package of research projects represented a comfortable mix of model development, understanding of pathway dynamics, prospective and retrospective experimental parameter measurements and geochemical studies. The proposals that were recommended for funding fit best into five major categories (with the proportion of the total projects for each category):

- (1) Impacts/Interactions/Linkages to Ecosystems: 10/21 proposals = 48%
- (2) Terrestrial Systems as Carbon Sources/Sinks: 4/21 proposals = 19%
- (3) Land/Ocean/Atmosphere Linkages to Climate Processes: 5/21 proposals = 24%
- (4) Human Dimensions: Economic Impacts and Policy Relevant Issues: 2/21 proposals = 10%
- (5) Educational Programs Relevant to Global Environmental Change Issues: 2/21 proposals = 5%

Development of an Integrated Research Site at the Gifford Pinchot National Forest:

One of the important aspects of the regional nature of NIGEC is the integration of research between regions. In an effort to meet this goal, WESTGEC is attempting to stimulate interdisciplinary studies at a new forest research site, the Wind River Canopy Crane Site (including a 200+ ft crane allowing access to the forest canopy) within the Gifford Pinchot National Forest in Washington. The Crane Site is being administered by Dr. Jerry Franklin from the University of Washington. One of our goals is to integrate several studies and measurements, especially on carbon flux, at the Crane Site with potentially comparable studies in several other NIGEC regions: Northeast (Harvard Forest tower site in MA; Howland Forest tower Site in ME), Southeast Region (a cypress swamp and slash pine site with towers in FL; Duke Forest tower site in NC), Midwest Region (Park Falls tower site in WI), Great Plains Region (a prairie wetland site in NE; Kanza Prairie site in KS), and the Southcentral Region (Temple C₃, C₄ grassland site in TX). These comparative studies will foster more cross-fertilization between the Regional Centers. By promoting research by a diverse group of researchers at the Crane Site, we can achieve two important goals for WESTGEC and NIGEC. First, we can develop a critical mass of research around which many different types of related forest ecosystem studies can be conducted. This process can create a site at which a more holistic (possibly ecosystem-level oriented) approach to forest research could be initiated. Second, this plan represents a unique opportunity to produce comparable carbon flux data on forest systems with different species in different parts of the continental U.S. concurrently. We are excited about this development and are working diligently to effect this collaboration.

Educational Outreach:

WESTGEC promoted Educational Outreach on global environmental change issues primarily by supporting two major educational programs this year.

- (1) Global System Science Curriculum (Lawrence Hall of Science): This project involves the development and testing of a 9 volume Global Systems Science curriculum for high school teachers. It is co-funded

by NSF and NIGEC. After "test driving" this curriculum in their classrooms, teachers from around the country attend a 3 week summer institute workshop at LHS to evaluate the success and potential problems with the newly developed curriculum in order to revise, update and improve the final product. One of the most valuable aspects of this program is their linkage to investigators at laboratories who are conducting ongoing research on issues relating to global environmental change.

(2) GLOBE Initiative: Early in 1995 WESTGEC sought and won a competitive grant from NASA/NSF/NOAA to conduct teacher training workshops for Phase 1 of Vice President Gore's national/international "GLOBE Initiative" (Global Learning and Observations to Benefit the Environment). The purpose of this initiative is to train K-12 teachers to guide students in the collection of weather and environmental data at their school sites, and is intended to serve at least two purposes. First, the program will instill in students a sense of stewardship over their environment. Second, the data being collected will be used by research scientists around the U.S. and around the globe to further the understanding of global climate change and environmental processes. The environmental data collected are uploaded onto the Internet, compiled at a centralized location and then made available to all participating schools to utilize in the development of environmental curricula. During FY 1994/95, WESTGEC hosted three GLOBE Initiative workshops: March 13-16 (38 teacher participants), June 20-24 (44 teacher participants), and June 27-30, 1995 (38 teacher participants). Eleven teachers from the June 27-30 workshop were awarded academic credit for their participation from the University Extension Program at U.C. Davis. All three of the teacher training workshops were very well received and generated tremendous enthusiasm among the participants who were all anxious to return to their classrooms to initiate their programs of environmental data collection. We look forward to having future involvements with the GLOBE Program.

World Wide Web Access: This year, WESTGEC has developed a World Wide Web Home Page. To learn more about the Western Regional Center's program, please visit WESTGEC's Home Page at the following WWW address:

<http://nigec.ucdavis.edu/regions/west>

Climate and Land Use Controls on Carbon Turnover Rates in Soils of the Sierra Nevada, California

Ronald Amundson and Yang Wang
University of California, Berkeley

Sue Trumbore
University of California, Irvine

Objectives: It is well established that the total mass of organic carbon (C) stored in soils is strongly related to climate, and that, in general, small changes in climate may cause dramatic changes in the total C stored in world's soils. However, the rate at which soils will re-equilibrate following an environmental change is poorly understood, and an understanding of these rates is critical if we are to understand feedbacks between global change and various C reservoirs.

The objectives of this study are to:

- 1) Determine the residence times of C in selected soils of the Sierra Nevada, California and establish their relationship to climatic parameters.
- 2) Determine the CO₂ exchange rate between soils and the atmosphere.
- 3) Predict how soil carbon in these and related soils will respond to a changing climate and land use.

Products: (1) detailed characterization of 3 undisturbed, and 2 managed, soil sites along a 2400 m elevation transect of the Sierra Nevada (vegetation density and species, soil C, soil organic matter ¹⁴C, bulk density), (2) detailed time series measurements of soil respiration rates, litter input rates, soil water content, soil water isotopic content, soil CO₂ amounts, isotopic composition of soil CO₂, isotopic composition of respired CO₂ at the above sites, (3) calculated effect of (a) climate on residence times of soil C and (b) the effect of soil management (irrigated agriculture or logging) on natural rates of soil C cycling and storage.

Approach: Three undisturbed, and two managed, sites have been selected and are the subject of ongoing study. Residence times of soil organic C are being calculated using a mass balance approach that assumes the soil is at

steady and that soil C residence time is:

$$\text{residence time} = \text{total soil C} / \text{rate of C decomposition} \quad (1)$$

where residence time is in years, total C is in g m⁻², and rates of decomposition can be approximated (see following discussion) from CO₂ evolution from soil surface (g C m⁻² yr⁻¹).

The major difficulty in solving equation (1) for a given soil is in quantifying rates of C decomposition. CO₂ produced in soils is from two sources (organic matter decomposition and root respiration):

$$\phi_T = \phi_R + \phi_H \quad (2)$$

where T = total CO₂ respired from a soil, R = CO₂ produced by root respiration, and H = CO₂ produced by organic matter decomposition. One of the most vexing problems in ecology has been accurately partitioning total soil respiration into the two sources. It has been shown that the two sources have distinct ¹⁴C contents: root respiration has ¹⁴C contents the same as atmospheric CO₂ while humus derived CO₂ is determined by the decomposing fractions of soil organic matter. Once the ¹⁴C content of humus derived CO₂ is determined, the residence time of soil organic matter can be determined using the following relationship:

$$\text{residence time} = 1 / \phi_T [(^{14}\text{C})_{\text{sr}} - (^{14}\text{C})_{\text{atm}}] / \text{C}_{\text{TL}} [(^{14}\text{C})_{\text{om}} - (^{14}\text{C})_{\text{atm}}] \quad (3)$$

where ¹⁴C_{sr} = measured ¹⁴C content of total soil respiration, ¹⁴C_{om} = ¹⁴C content of humus derived CO₂, ¹⁴C = ¹⁴C of atmospheric CO₂, C_T = total soil C. We will directly measure all these parameters at each site and use the values to estimate the residence time of soil C.

In equation 3, the most difficult parameter to estimate is ¹⁴C_{om}. We will use two approaches to determine the value of this parameter: (1)

measure $^{14}\text{C}_T$ in the winter or early spring when root respiration is minimal and (2) incubate soil samples in the lab (after roots are removed) to determine directly the ^{14}C of the humus derived CO_2 .

As part of our research, we have also been investigating the processes controlling the $^{18}\text{O}/^{16}\text{O}$ of soil CO_2 ($\delta^{18}\text{O}$ value) as a means to use this isotope signature as an additional tool in atmospheric CO_2 modeling. We have a set of measurements of the $\delta^{18}\text{O}$ values of soil water and CO_2 .

Results to Date: Our time series measurements of soil and environmental measurements are now at their midpoint, and detailed compilations have not been made. In Figure 1, we illustrate the C in the Fallbrook (470 m), Musick (1240 m) and Chiquito (2890 m) soils. Carbon in the low density fractions increases with elevation and, from our previous studies, is believed to have a shorter residence time than the remaining C. We expect these differences to reveal themselves in the residence times we will eventually calculate for these soils.

Soil CO_2 fluxes (Figure 2) have been measured approximately monthly since August 1994. Our preliminary data shows that the mid-elevation soil has the highest total respiration, which corresponds to its high soil C content and its high plant density (which has been quantified but has not yet been analyzed for this publication).

We have begun analyzing the results of our measurements of the relationship between the oxygen isotopic composition of soil CO_2 , respired CO_2 , and soil water. Previous forays into this field have resulted in conflicting interpretations. We investigate this parameter as it involves little additional work in our overall research plan and because it may provide a means of better incorporation the $\delta^{18}\text{O}$ value of soil CO_2 into global atmospheric CO_2 budgets.

Our results so far indicate that (1) the $\delta^{18}\text{O}$ value of soil CO_2 is in oxygen isotopic equilibrium with soil water (Figure 3), (2) no diffusion effects are noted due to the long residence times (10^2 to 10^3 hours) of the soil CO_2 at most depths, and (3) the $\delta^{18}\text{O}$ value of respired CO_2 is the same as CO_2 in equilibrium with soil water and it is not depleted in ^{18}O as some previous researchers have assumed.

Publications:

Amundson, R. and Y. Wang. 1995. The relationship between the oxygen isotope composition of soil CO_2 and water. In: International Symposium on Isotopes in Water Resources Management. International Atomic Energy Agency, Vienna Austria (in press).

Presentations:

Amundson, R. and Y. Wang. 1995. The relationship between the oxygen isotope composition of soil CO_2 and water. International Symposium on Isotopes in Water Resources Management. International Atomic Energy Agency, Vienna, Austria. March 20 - 24, 1995.

Other products: Effect of climate and land use on microbial populations and metabolic capacities. Ms. Teri Balser. PhD Research Project, University of California. 1995; Effect of climate and land use on the ^{14}C content of humus derived CO_2 . Mr. Troy Baisden. PhD Research Project, University of California. 1995.

Student participation: Teri Balser (Phd) 15%; Troy Baisden (PhD) 100%.

Figure 1. Changes in carbon content in A horizon in soils along the Sierra Nevada elevation transect.

Figure 2. Soil respiration for the 3 undisturbed soils. Total CO_2 production by the soils is greatest at mid-elevation and decreases with either increasing, or decreasing, elevation.

Figure 3. Relationship between O isotope composition of soil CO_2 and water for various soil depths and locations. Lines show theoretical isotopic equilibrium at various temperatures and suggest that isotopic equilibrium is approached for most samples.

Estimating the Costs of Climate Change on a Regional Scale

Richard A. Berk and Robert G. Fovell
University of California, Los Angeles

Objectives: Policy responses to possible global climate change are in part premised on benefits and costs. Yet, it is extremely difficult to obtain reasonable cost estimates from observable behavior because the climate change of concern is in the future. In the present, only proxies can be observed. Alternatively, contingent valuation (CV), a relatively new and controversial tool, may help provide at least one way to estimate the costs of various policy options.

In this project, we are applying CV to climate change and attempt to remedy some of the problem with CV. In particular, we are building on earlier work funded by NSF (Berk and Schulman, 1995) and employing factorial survey methods to elicit from representative samples of Los Angeles residents estimates of value placed on various climate change possibilities. The climate change scenarios, in turn, are being constructed so that a substantial fraction of them will represent a reasonable guess about how climate change might materialize in Southern California.

Products: We will produce estimates of value respondents place on various climate change possibilities and technical improvements that can be exploited by others. Our instrument, that can be easily generalized to other locales, will also be available. Finally, we will produce empirically based descriptions of local climate that will be of interest in themselves.

Approach and Progress to Date: There are two parallel aspect to the project: 1) the construction of plausible climate change scenarios for the Los Angeles Area and the development and fielding of a survey which elicits "willingness to pay" estimates from representative samples of respondents. Each will be discussed in turn.

"Climate" has no simple definition. Still, two parameters that can help define the climate of a given location are temperature and precipitation. The annual averages as well as the seasonal variations about the averages are important. With regard to temperature, we believe the public

is more sensitive to maximum daily temperature than minimum or daily mean temperature. Data regarding daily maximum temperatures and precipitation accumulations for Los Angeles Airport (LAX) (representing the coast) and Pasadena (representing the inland valley population) were obtained from the National Climatic Data Center. Both locations have nearly unbroken data records extending back to the early 1940s.

As required by the study, the coastal and valley area are handled separately. In addition, we initially considered handling temperature and precipitation separately, constructing a pair of two-dimensional geometric spaces with axes defined by seasonal means (e.g., average winter daily maximum temperature or precipitation vs. average summer daily maximum temperature or precipitation). We believe, however, that it is more appropriate to handle the seasons separately, as temperature and precipitation jointly influence the public's perception of what constitutes a seasonal climate. Thus, for the winter season (defined as December through February, a traditional subdivision, but one supported by the LAX data), the 2D geometric space is average daily maximum temperature vs. average monthly precipitation accumulation. The distribution of seasonal averages in this space defines the normal degree of variation experienced at the location (coast or valley).

Summer arrives relatively late on the West Coast, and an examination of the data suggested a 92 day period spanning July through September as an adequate local definition of this season. However, because summer precipitation is quite infrequent, the summer season has to be handled differently. A number of possibilities for the summer's second geometric dimension were considered (including measures of temporal temperature persistence or "heat waves") and the option of keeping the summer season unidimensional has also been explored. The final decision on the handling of the summer season will be made shortly.

As at least some segments of the public may have difficulty assessing quantitative questions (such as "How would you feel if the temperature increased by X degrees") in the absence of

context, we decided to explore the possibility of using spatial locales whose existence and *present* climate characteristics are generally known to the public as proxies representing possible *future* climate scenarios at their locale (coast or valley). This allows the survey to ask questions like "How would you feel if the temperature and precipitation here changed in such a way, making the future climate here more like the present climate of -- (some other known location)".

Numerous candidates for proxy locales were considered and analyzed, with long term average seasonal data having been computed. In the best case scenario, a sufficient number and variety of proxy locales would be identified such that their seasonal means, represented as points in the target locale's geometric space, would be generally distributed throughout the space. That is, they would represent locations that are now either warmer or cooler and wetter or drier than the present target locale. We made a conscious decision to utilize only California locales as proxies, which is possible owing to California's substantial climatological diversity and the public understanding of that variation.

While working to build our survey climate scenarios around plausible future possibilities, we are refining the survey instruments employed in our earlier NSF-funded research. The goal is to include survey items that will allow us to untangle several different sources of value: different kind of use and non-use value. Rather than asking people abstract questions about what they value or trying to elicit sensible answers from the sound-bite language too often used in questionnaires, we include several different questions following each climate scenario addressing different aspect of the hypothetical climate change.

The survey instrument will be ready for pilot testing by the end of the summer and then fielded on a probability sample of Los Angeles residents early in the fall.

The Relationship Between CCN Chemistry, CCN Sources, Cloud Microphysics and Precipitation in the Eastern Sierra Nevada

Randolph D. Borys, Douglas Lowenthal and David Mitchell
Desert Research Institute

Objectives: This is the completion of the second year of a two year combined field sampling and modeling study on the effect of different sources of cloud condensation nuclei (CCN) on snowfall rates. Originally the intent was to conduct the study in the Sierra Nevada. Because of the loss of access to the proposed site, we moved the operation to the Desert Research Institute's Storm Peak Laboratory in Steamboat Springs, Colorado. The results of the study should be generically applicable to mixed phase, precipitating clouds.

The primary objective of this study is to establish the relationships among chemistry and sources of CCN, cloud droplet concentration and size distribution, and snowfall rate. This objective has been addressed by performing three tasks:

Products:

- 1) Experimentally establish a relationship between changes in cloud droplet size and snowfall rates. The hypothesis to be tested is that CCN concentrations determine droplet size for a given LWC and have an effect on snowfall rates.
- 2) Experimentally determine the dependence of the cloud droplet size distribution on aerosol sources. Relative contributions of natural and anthropogenic sources to CCN will be determined using receptor modeling by comparing the chemical composition of the cloud water with that of emissions from known upwind sources.
- 3) Using the snow-growth model with field data, determine whether the observed dependence of snowfall rates on cloud droplet size is consistent with the predicted dependence. Consistency between observations and theory will allow us to quantify the impact of changing CCN levels on snowfall rates.

Approach: We once again conducted our second year field effort at DRI's Storm Peak Laboratory (3220m MSL) in northwest Colorado. This site has proved an excellent location for the

type of research we are conducting. During the period 13-28 January, 1995 we collected over 50 sample sets as described in our proposal. Cloud droplet size distributions were measured with a PMS FSSP-100. Concurrently, bulk cloud water was collected using cloud sieves for later detailed chemical analysis and precipitation rate was measured with a sensitive electronic precipitation gage specifically fabricated for this project. The precipitation (in the form of snow) was also monitored using a new instrument developed with support from this grant. This device, the DRI Snow Video Spectrometer, continuously monitored on video tape, images of snow which fell naturally onto a clear Mylar tape which advanced in front of the camera, providing a record of the size, number and habit of the snow. The snow crystals were also melted prior to advancing the film for a new collection allowing accurate measurement of the mass of each crystal. Figure 1 is a schematic of the instrument. These measurements will provide us with the necessary information to stratify the data by mean ice particle size, a necessary parameter for use in the snow-growth model. These techniques allowed us to measure and collect samples over periods of 10 minutes in duration, allowing the minimization of variability in cloud and snow parameters with time.

To date we have analyzed the cloud water samples for inorganic ions, pH and conductivity. The remaining sample has been sent to the Rhode Island Nuclear Science Center for analysis by neutron activation analysis for the trace elemental species needed for the receptor modeling. We expect these analyses to be completed in mid September. All of the cloud droplet and precipitation rate data have been reduced. We are still in the process of analyzing the snow crystal video imagery. We eventually hope to have this automated for future work.

Results to Date: We have assembled and analyzed the data we have to date. The following figures demonstrate the relationships we observed between droplet number and droplet size, droplet number and droplet sulfate, droplet size and droplet sulfate, and finally

combining these data the relationship between droplet size and snowfall rate, both predicted by the snow-growth model and observed.

We stratified the data into three different categories of cloud liquid water content (LWC); $0.1 < 0.2 \text{ g/m}^3$, $0.2 < 0.5 \text{ g/m}^3$, and $0.5 < 1.0 \text{ g/m}^3$. Figure 2 shows the relationship between droplet size and droplet number in the highest LWC interval. This interval was also associated with the largest precipitation rates. We see how the mean droplet diameter (weighted by number concentration) decreases with increasing droplet concentration. The slope of the linear regression increases with increasing LWC. The droplet number concentration is also a surrogate measure of the number of cloud condensation nuclei (CCN) which are being activated in the cloud under study. Our hypothesis assumes the total LWC is primarily fixed by the thermodynamic conditions of the cloud, and that increasing numbers of CCN should cause a shift in the mean droplet size to smaller diameters. This is evident in Figure 2.

One hypothesis we proposed to test was how differing sources of CCN affected the cloud droplet population. Figure 3 shows the relationship between sulfate measured in the cloud water, expressed as mg m^{-3} in the air, and the droplet concentration. The strongest relationship was observed for the highest LWC cases, as shown in this figure. We see that there is a significant positive relationship between the sulfate loading and the droplet concentration. We have not determined the source of the sulfate as yet, but prior studies done at this location have shown that greater than 90% of the sulfate is pollution derived and that 65% of the pollution sulfate is a result of coal combustion. From Figures 2 and 3 it is clear that as droplet diameter decreases as a result of increased numbers of CCN producing higher concentrations of cloud droplets (Fig. 2), these higher droplet number concentrations are associated with elevated levels of sulfate. Increasing the sulfate loading reduces the mass mean droplet diameters.

Changes in the mean droplet size were hypothesized as being key in determining the snowfall rate from the mixed phase clouds we studied. This results from the effect of changing droplet size on the efficiency of ice crystal riming of cloud droplets. This snow growth mechanism is expected to account for about 50% of the

annual water content of the snowfall produced by these clouds. The snow-growth model predicts the snowfall rate given cloud liquid water content, mass mean cloud droplet diameter and ice particle concentrations and sizes. The model was initialized using a vertical distribution of LWC (in this case in the range 0.1 to 0.2 g/m^3) and ice particle size distributions using cases from the literature for wintertime clouds in eastern Colorado and Canada. Varying only the mass mean droplet size, and using the same range of LWC measured at SPL, the model output of snowfall rate at SPL is plotted on our field data in Figure 4. Although there is a great deal of scatter in our data the regression line has nearly the same slope and intercept as the model prediction.

Even though we have presented a small data set from one field season, we feel the conclusions that can be drawn are strongly indicative of our hypothesis that increasing levels of CCN, likely derived from pollution sources, can have a negative effect on snowfall rates. This conclusion, though tentative at this time, has strong implications in the arid West. We will summarize these findings in publications forthcoming once we have the final chemical analysis of the cloud water completed. No new publications have arisen from this research as yet. We have requested a one-year no-cost extension to complete the final analysis and reporting.

Students: We were not able to obtain another student after the departure from our program of Ms. Sherri Knopf last year. However, one of the PI's, Dr. David Mitchell, received his PhD from the University of Nevada (listed below) while supported on this contract. His model was integral to the research objectives.

Publications:

Mitchell, D.L. Use of mass- and area-dimensional power laws for determining terminal velocities of cloud and precipitation particles. *J. Atmos. Sci.* (in review, 1995).

Mitchell, D.L., 1995: A simple expression for accurately calculating precipitation fallspeeds for any particle type. Preprints, Conf. on Cloud Physics, Amer. Meteor. Soc., Dallas, TX, January 15-20, pp. 46-49.

Mitchell, D.L., 1995: An analytical model predicting the evolution of ice particle size distributions. Ph.D. dissertation, Univ. of Nevada, Dept. of Physics, 171pp.

MOLECULAR CRYSTAL SPECTROSCOPY

Figure 2

Figure 4

Figure 3

Environmental Information from Isotopic Composition of Hydrogen and Carbon in the Western USA and Alaska

Samuel Epstein
California Institute of Technology

Objectives: Basically, our overall objectives have been to use hydrogen, oxygen and carbon isotope record to obtain global climatic temperatures and CO₂ concentrations for the past hundreds of years using trees from many locations including those in the Western United States. In addition, we were able to obtain carbon and hydrogen isotope records for the past thousands of years using old trees and fossil wood in a few special places like the White Mountains of California and the North Slope of Alaska. These data could provide some information about the long-term climatic trends.

The isotopic composition of hydrogen and carbon in tree rings respond to certain environmental components. The D/H ratio in cellulose extracted from plants is largely determined by the D/H ratios of the meteoric water incorporated by the plants. Since the D/H ratios of meteoric water are systematically related to the temperature at the site of precipitation, the D/H ratio in trees can be used as a proxy indicator of the past climatic temperature.

The isotopic composition of carbon in the trees reflects primarily the isotopic composition of carbon in the CO₂ as well as to such factors as: The moisture content of the atmosphere and in the soil, the species of the plants and the density of the trees in the area which can create an unusually low ¹³C - CO₂ due to respiration. The tree ring width can provide important climatic information most directly in term of environmental aridity. All the above tools have been extensively used for climatic research with the exception of the isotopic analysis of hydrogen, which is the most sparsely available in spite of its obvious importance as a recorder of climatic temperatures. Our laboratory has been involved in retrieving isotope data from trees, off and on, for the past twenty years. We have shown that there is a direct relationship between the δ D of unexchangeable hydrogen in tree cellulose and the isotopic composition of the water utilized by the trees. Thus the tree records faithfully, the isotopic composition of the water which is related to the environmental temperature. This

relationship has been confirmed more elegantly by White et al 1994 in their study the various factors that might effect this relationship. The relationship between δ D and temperature is $T^{\circ}\text{C} = 0.123 \delta\text{D} + 19.1$.

Products: In the past year or so, with the help of WESTGEC funds, my postdoc, Dr. Feng, and I have obtained some very interesting data resulting in papers that have been published or have been accepted for publication or are in review: a) our papers on the "Climatic Implications of an 8000-Year Hydrogen Isotope Time Series from Bristlecone Pine Trees," was published in Science (Feng and Epstein, 1994), b) another paper on the "Carbon Isotopes of Trees From Arid Environments and Implications for Evolution of the Atmospheric CO₂," appeared in the most recent journal of the *Geochimica et Cosmochimica Acta* (1995), c) a third paper on the "Climatic Temperature Records in Tree Rings," was accepted by *Geochimica et Cosmochimica Acta*, and d) a fourth paper on the "Climatic Trends From Isotopic Records of Tree Rings: The Past 100 to 200 Years," is in review.

Approach: Paper (a) reports a continuous δ D record in tree rings between 8000 years B.P. and the present, in 50-year intervals using a combination of three tree segments taken from three bristolcone pine trees from White Mountain, California (Figure 1). This adjusted trend in the δ D record demonstrates that generally a cooling trend occurred between 8000 and 2000 BP occurred, representing roughly a 5°C change. The question arises, whether these data represent a long-range climatic cycle involving thousands of years is characteristic of our Earth's climatic history? A question that is worth pursuing. This paper received a lot of interest, primarily because it might suggest the possibility of a climate cycle which may include an actual increase in temperature in the near future of the Earth. We are now analyzing the δ D and ¹³C/¹²C ratios of cellulose from fossil wood collected from a dry lake (Lake Emma in Colorado) which is dated between 9000 to 4000 years BP. The preliminary data suggests that a δ D trend similar

to that found in White Mountain, California is also present in the Lake Emma area.

The second paper (b) entitled, "Carbon Isotopes of Trees From Arid Environments and Implications for Evolution of the Atmospheric CO₂," deals with the relationship between the δD , $\delta^{13}C$ and ring width in trees from mostly arid environments. The use of trees from arid environments eliminates the "canopy effect" on the $\delta^{13}C$ record in the trees. This effect exists in areas of dense vegetation growth and causes an unusually low $\delta^{13}C$ value in the trees due to the availability of night-time respired CO₂ which has a much lower $\delta^{13}C$ value than normal atmospheric CO₂. The photosynthetic fixation of CO₂ in the morning results in an unusually light $\delta^{13}C$ in the wood due to contamination with respired CO₂. Thus, the plants grown in forests will have a lower $\delta^{13}C$ than those which grow in sparsely vegetated areas.

The isotopic composition of carbon in plants contains long-term trends and high frequency variations. The long-term trends could be due to the introduction of low $\delta^{13}C$ carbon dioxide originating from the combustion of fuels ("anthropogenic effect") or could reflect just any other long-term variation such as the general increase in the world biota, in which case there could be a long-term increase in the $\delta^{13}C$. The high frequency variations in $\delta^{13}C$ can be shown to be related to the variations in the amount of precipitation. The variation in the amount of precipitation in arid areas is also reflected in the width of the tree rings (Fig. 2). Thus, the relationship between the $\delta^{13}C$ and the width of the tree ring is shown to be very strong. The combined $\delta^{13}C$ and tree ring width can be characteristic of the degree of aridity of the tree sites. In moderately arid areas, such as the Santa Monica Mountains in California, the δD and $\delta^{13}C$ records are also related to climatic change.

In conclusion, the combination of δD , $\delta^{13}C$, and tree width data will provide information about climatic temperature, relative humidity, rainfall, and the concentration and isotopic composition of atmospheric CO₂. This type of information about our past environments may well be important to our estimates of the future conditions of the Earth's surface.

Results to Date: A paper in press (c), "Climatic Temperature Records in Tree Rings," deals

primarily with the accuracy of the climatic record obtained from δD values in tree rings. We feel that this paper adds further merit to the existence of a good relationship between the δD values and recorded temperatures. Its purpose is to show the best way to extract climatic temperature information from the δD records obtained from trees. Figure 3 shows the direct δD vs. temperature relationship using a running average of 15 years for the δD data vs. a five-year running average for the recorded temperatures. This smoothing process enhances the relationship between the isotopic composition of deuterium and the recorded temperature. The coefficient for this temperature change is approximately 8% per 1°C.

Manuscript (d), "Climatic Trends From Isotopic Records of Tree Rings: The Past 100 to 200 Years," reports results which are shown in Figure 4 and which contains all of the data reported in this paper. This figure shows the δD record of 14 trees collected randomly from worldwide sites, with the δD records dating back as far as the 1780's in some of these trees. These trees came from areas of highly variable climatic conditions, ranging from warm and semi-arid locations, like the Sinai Desert and the Santa Monica Mountains in California, to wet locations like the Olympic Peninsula in Washington State. Additionally, these samples included trees from mountainous areas like the White Mountains in California, the Olympic Peninsula in Washington State, and the Rocky Mountains of Colorado, as well as from locations of low relief such as Wisconsin, New York, Cambridge in England, and Manitoba in Canada. The main point of this paper is to illustrate the importance of having a lengthy climatic record which is not available to us in the ordinary historical records. The availability of a long record provides additional significant information which benefits the total record. For example, these long records show that there was a rather smooth rise in the temperature over almost all of the areas represented by the trees until 1920. After 1920, the fluctuations in the δD values increased, as if some feedback mechanism responded to the lengthy period of warming. A dramatic example of this possible feedback mechanism is displayed in the δD record of the Kenya. For over 100 years, the temperature in that area increased until about 1920, at which time some serious drought conditions existed. However, at about 1960, there was a marked decrease in the δD indicating a dramatic cooling and a sharp increase in the amount of precipitation in that

area. The record reported by Lamb (1982) showed that the level of Lake Victoria in that country rose by two meters at the same time. Considering the enormous size of Lake Victoria, this represented an unusual deviation from the climatic record of that area that had existed for at least 100 years. Significantly, this large climatic change was recorded in the isotopic composition of the Kenya tree which was a result of a loss of the δD enriched moisture which preferentially fell on Lake Victoria. Obviously, this event made an important impact on the area's ecosystem. To a lesser degree, similar climatic temperature changes may have occurred in many different locations, but with less dramatic isotopic changes. Nevertheless, this suggests the merit of further investigations of trees which are as old as 200 years and duplicating this data using neighboring tree location. We will make every effort to obtain the appropriate samples from California and particularly from the western part of the United States where trees like the ancient Sequoia are available. This is obviously a very interesting question to investigate whether there was a warming spell in the 19th century.

The ability to get paleotemperatures over long periods of time in different locations representing a large range of climatic conditions is essential to the understanding of the factors associated with global climate change. This sort of data can serve as a guide for those trying to develop a general global climate model, as well as for those who are evaluating the conditions of plant growth from pollen research.

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(Figure 1) The δD record from three bristlecone pines from the White Mountains, California.

(Figure 2) A comparison of the time series of the 5-year ring width with the $\delta^{13}C$ for the bristlecone pine. Both time series have been detrended and smoothed using a 15-year running average.

(Figure 3) Plot of the δD the tree from the Olympic Peninsula in Washington State versus a 5-year average of the mean annual temperature in five locations. Top: for the original data set; bottom: for the 15-year running average of both variables.

(Figure 4) δD time series for 14 trees collected randomly in the northern hemisphere (except for tree from Kenya). The straight lines illustrate that relatively smooth progressive warming occurred through the 19th century and the early part of the 20th century. From top to bottom, the δD values become more and more negative, and the slope of the straight line gradually increases when moving from warm to cold locations. The trees from Siberia and Alaska are exceptions.

Physics and Parameterization of Cirrus Clouds

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Objectives: This is the progress report for the project "Physics and parameterization of cirrus clouds grant" This research has been directed towards understanding of physical properties of cirrus clouds and their influence on large scale environment. The broad research topics have been: radiative properties of cirrus clouds and single scattering properties of non-spherical cirrus ice crystals.

Products: The members of the project submitted papers to refereed journals and major conferences.

We have continued our work on theoretical properties of cirrus ice crystals and numerical methods for light scattering by non-spherical ice particles. The new version (5a) of the Fortran program DDSCAT (Discrete Dipole Approximation) has been released. This version provides enhancements in both numerics and physics. The INTERNET light scattering library SCATLIB has been completed and the light scattering codes are distributed this way.

We have worked on dehydration of the upper troposphere and lower stratosphere by subvisible cirrus clouds near the tropical tropopause. We have completed our analysis of the data from the Central Equatorial Pacific Experiment designed to study tropical cirrus clouds. Multifaceted datasets - Navy NOGAPS synoptic global analysis, aircraft, and oceanographic - have been employed.

Approach: We have combined theoretical, experimental and modeling approaches to study radiative effects of cirrus clouds and their scattering properties.

Results to Date: Eric J. Jensen et al (1995) report on "Dehydration Of The Upper Troposphere And Lower Stratosphere By Subvisible Cirrus Clouds Near the Tropical Tropopause". The extreme dryness of the stratosphere is believed to be caused by freeze-drying of air as it enters the stratosphere through the cold tropical tropopause. Over the past two decades, investigations have been focused on

dehydration occurring at the tops of deep convective cloud systems. However, recent observations of a ubiquitous stratiform cirrus cloud layer near the tropical tropopause suggest that the possibility of dehydration as air is slowly lifted by large-scale motions should be considered. We have used a detailed ice cloud process model to evaluate the potential dehydration of the tropical tropopause region by in situ formation and precipitation of ice crystals. Simulations of ice cloud formation in the cold troughs of gravity waves (wave periods of 1 - 2 hours) indicate that large numbers of ice crystals will likely form due to the low temperatures and rapid cooling. As a result, the crystals do not grow larger than about 10 microns, fallspeeds are no greater than a few cm/s, and little or no precipitation or dehydration occurs. However, ice clouds formed by large-scale vertical motions (with lifetimes of a day or more) should have fewer crystals and more time for crystal sedimentation to occur, resulting in water vapor depletions as large as 1 ppmv near the tropopause. We suggest that slow vertical updrafts near the tropopause over the western Pacific may provide a large fraction of the troposphere-stratosphere mass flux, and the formation of thin cirrus in this rising air may account for the dehydration.

Cirrus scattering properties:

In Draine and Flatau (1994) the discrete dipole approximation (DDA) for scattering calculations is reviewed, including the relationship between the DDA and other methods. In Flatau (1994) we discuss a single scattering parameterization of scattering by non-spherical particles compatible in simplicity with bulk-type microphysics schemes currently used in mesoscale and global numerical prediction models. In Mackowski and Flatau (1994) we show how to calculate extinction and absorption cross sections for fractal particles. These findings and resulting codes are now being distributed via the SCATLIB Internet site (<http://atol.ucsd.edu/>). SCATLIB is a library of light scattering codes. Information related to scattering on spherical and non-spherical

particles is collected. Reviews of relevant numerical methods is provided as well as information about the past and future meetings related to scattering.

Cirrus dynamics and modeling - Tropical Pacific

Members of the project participated in the Central Equatorial Pacific Experiment (CEPEX) (NSF and DOE funding). Flatau (1993) reports on a unique set of radiative measurements collected on board of NOAA NR42 P3 aircraft during CEPEX between March 11 and April 4 of 1993. W. D. Collins, D. Lubin, P. J. Flatau, B. Subasilar, and C. P. Weaver (1993) report on the cirrus cloud forcing at the surface as determined from Eppley pyrgeometers on the NOAA P-3 and a Fourier transform infrared spectroradiometer (FTIR) on the R/V Vickers. Flatau, M. and Flatau, P. J. and Phoebus, P., (1995) performed synoptic overview of CEPEX period. Jensen, E. J. et al (1994) performed one-dimensional radiative transfer calculations to evaluate the impact of cirrus clouds on the tropical radiation budget.

Collins, W. D., F. P. J. Valero, P. J. Flatau, D. Lubin (1995) report on the radiative effects of tropical clouds at the tropopause and the ocean surface. The estimates have been performed using in situ measurements from the Central Equatorial Pacific Experiment (CEPEX). The effects of clouds is distinguished from the radiative effects of the surrounding atmosphere by calculating the shortwave and longwave cloud forcing. At the tropopause, the shortwave and longwave cloud forcing are nearly equal and opposite, even on daily time scales. Therefore the net effects of clouds is small compared to other radiative terms in the surface-tropospheric heat budget. This conforms the statistical cancellation of cloud forcing observed in Earth radiation budget measurements from satellites. At the surface, the net effect of clouds is to reduce the energy absorbed by the oceans. The CEPEX observations show that the atmospheric cloud forcing is nearly equal and opposite to the surface forcing and approaches 100W/m^2 when the surface is 303K.

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Global Warming Trends and Internal Climate Oscillations: Detection and Modeling

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Objective: To decompose the existing multi-decadal records of surface temperature, sea-level pressure and sea-level height into their principal components, with respect to spatial and temporal variability, and to relate these dominant statistical features to bio-geochemical, physical, and dynamic mechanisms, natural or connected with humanity's activities.

Product: Evaluation of climate variability on interdecadal time scales and of the implications of this variability for the reliable detection and prediction of systematic global warming trends.

Approach: A crucial question connected with global change is the reliable detection of a systematic warming trend in global surface temperatures, on the time scale of decades to a century. This detection is rendered difficult by the presence of substantial variability on time scales both shorter and longer than the one of interest. Greenhouse trace gases have increased rapidly over the last century, e.g., carbon dioxide (CO₂) by about 25%. Documented temperature change over the same time interval is only about 0.5°C; this is both smaller than climate models would suggest, and marred by non-negligible uncertainties. These uncertainties are due to temperature variability on other time scales, and to the possible effect of climatic mechanisms unrelated to trace gases. Identifying this variability both by observational and modeling techniques is a prerequisite to accurate detection and prediction of anthropogenic climate change.

Advanced tools for the statistical analysis of climatic oscillations, and of their spatial patterns, have been developed by M. Ghil and collaborators in connection with paleoclimatic studies (Vautard and Ghil, 1989) and with studies of low-frequency atmospheric variability (Ghil and Mo, 1991a, b). Singular spectrum analysis (SSA) is a generalization of spectral analysis which uses data-adaptive filters and is particularly well suited for the study of nonlinear, slightly-irregular oscillations. Its adaptive prefiltering properties yield fruitful combinations with other spectral techniques, such as the maximum-entropy method (MEM: Penland *et al.*,

1991) and the multi-taper method (MTM: Thomson, 1982; Vautard *et al.*, 1992).

Results to Date: In earlier work supported by this grant, Ghil and Vautard (1991) applied SSA to globally and hemispherically-averaged surface temperatures (Bottomley *et al.*, 1990; Folland *et al.*, 1990), separating a nonlinear trend plus a small number of interannual and interdecadal modes of variability from background noise. The oscillatory components have combined (peak-to-peak) amplitudes of 0.2°C, and thus limit our ability to predict whether the inferred secular warming trend of 0.005°C yr⁻¹ will continue. Furthermore, warm phases of the oscillatory components have contributed significantly to the high global temperatures since 1976. This raises the possibility that temperatures may become temporarily cooler due to natural oscillations, masking warming due to the long-term trend. Elsner and Tsonis (1991) and Tsonis and Elsner (1992) commented on the Ghil and Vautard analysis, which was vindicated by Allen *et al.* (1992a, b) and other authors.

Ongoing work in this area is aimed at refining the observational understanding of the interdecadal oscillations, based on longer instrumental time series (Manley, 1953, 1974) and on the study of their spatial patterns. Dettinger *et al.* (1995b) show a 10-year oscillation, but no trend for the spatial EOF associated with mean U.S. temperatures, while the EOF representing an East-West seesaw exhibits both a trend and a 23-year oscillation. This suggests the presence of different modes of interdecadal behavior for the Northern Hemisphere (NH) as a whole than for the two major NH ocean basins separately. Earlier results on the three-century long Central England temperature (CET) record (Ghil, 1994) appear in Martinson *et al.* (1995). The full results have just appeared in *Science* (Plaut *et al.*, 1995) based on the Parker *et al.* (1990) reworking of Manley's (1974) CET data. They show interdecadal peaks near 25 and 15 years, as well as a temperature drop of about 1°C around 1700; the latter perhaps associated with the Maunder minimum.

The extension of SSA-MEM for use as a predictive tool based on MEM-associated auto-

regressive models has been applied to the Southern Oscillation index as a prototype case for climate prediction (Keppenne and Ghil, 1992a, b). For this phenomenon, the prediction method is shown to have valuable skill out to 30–36 months. Vautard *et al.* (1992) have applied SSA-MEM prediction to the IPCC consensus time series (Houghton *et al.*, 1990) and foreshow slight cooling of global surface air temperatures into the middle of the 1990s, before subsequent further warming. A comparison between the SSA approach and other advanced statistical methods for the analysis of U.S. surface-air temperatures is provided by Handcock and Wallis (1994) and Keppenne *et al.* (1994). Software for the application of SSA, MEM and MTM to other climatic time series has been provided by Dettinger *et al.* (1995a). The Plaut *et al.* (1995) work shows CETs decreasing toward the end of this decade and rising again until the middle of next.

Multi-channel SSA (M-SSA) has proven useful in studying the nonlinear interaction of multiple time and space scales in climate phenomena. Subharmonics and frequency locking arise when internal frequencies interact with each other and with the annual cycle (Jin *et al.*, 1994). Using COADS data for sea-surface temperatures (SSTs) and zonal winds, Jiang *et al.* (1993, 1995) showed that a dominant Quasi-Quadrennial peak could be separated from a secondary Quasi-Biennial peak, thus refining the single-channel SSA results of Rasmusson *et al.* (1990). These M-SSA results will be extended into the interdecadal range.

Modeling research on the explanation of interdecadal oscillations, as detected by Ghil and Vautard (1991) and Vautard *et al.* (1992), has been initiated. We strongly suspect that these 20–25 year oscillations manifest in surface temperature records involve the extratropical, thermohaline circulation (THC) of the oceans (Ghil and McWilliams, 1994). Changes in thermal structure of the North Atlantic, down to 2000m, over a few decades have been documented recently (Levitus, 1989) as well. A bifurcation study of a simple ocean model forced by prescribed surface temperatures and salinity fluxes (Quon and Ghil, 1992) has yielded insight

into THC dynamics, especially the transition between the asymmetric, one-cell THC of the present Atlantic ocean and a symmetric, two-cell circulation. The continuous transition via increasingly asymmetric two-cell circulation's can be understood as a function of Rayleigh number and the strength of the salt flux forcing. When the salt flux strength is sufficiently large, the system undergoes a Hopf bifurcation leading to sustained, long-period oscillations (Quon and Ghil, 1993, 1995). This bifurcation is robust to changes of the spatial structure of the salt-flux, contrary to what had been claimed in some general circulation model studies (Weaver *et al.*, 1993).

Interdecadal changes in sea-ice cover have also attracted considerable attention (Mysak *et al.*, 1990). Sea ice insulates high-latitude oceans from intense atmospheric cooling and thus affects their temperature. Freshwater flux produced by sea ice melting or freezing modifies their salinity. Sea ice is thus involved strongly in the two major processes that control the THC. Yang and Neelin (1993) showed that coupling a nonlinear, thermodynamic sea-ice model with a zonally averaged ocean model similar to that of Quon and Ghil (1992, 1995) could produce interdecadal oscillations. The mechanism involves a cycle of melting and freezing of sea ice and associated density effects on the THC, and provides a consistent demonstration that THC-sea-ice interactions can introduce new interdecadal phenomena not present in the ocean alone. Yang and Neelin (1995a,b) found that thermal insulation by sea ice stabilizes the THC, while the freshwater flux associated with freezing or melting increases the effective inertia of the system; the latter tends to slow down THC response to long-time scale external forcing. Analytical modeling used to supplement the numerical work shows why the fresh water flux due to sea-ice melting associated with warming affects the adjustment processes of the coupled ice-ocean system, but not the end result. The long-term response is more strongly affected by the sea-ice insulation effect.

Student participation: Fei Chen 25%, Ph.D. (completed); Ning Jiang 75%, Ph.D.; Yurdanur Sezginer 25%, Ph.D. (completed).

Global Warming and Carbon Dioxide: An Experimental Investigation of Ecologically-Mediated Feedbacks from a Terrestrial Ecosystem

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Objectives: The overall objective of this project is to quantify and understand the effects of increased downward heat flux (such as would be experienced under global warming) on the carbon cycle of a montane meadow ecosystem. Although there are many factors which will change under global warming (including ambient CO₂ concentration, air temperature, and precipitation), this project focuses on the effects of increasing the downward flux of infrared radiation (which can be predicted with greater certainty than effects such as air temperature or precipitation).

This objective includes development (through statistical and mathematical modeling) of detailed experimentally testable hypotheses about the mechanisms that underlie observed effects. This will deepen our understanding of how climate change will effect net CO₂ exchange rate in ecosystems.

Products: (1) A quantification of heating effects on the carbon cycle, and thus of any possible CO₂ feedback to climate. (2) A detailed understanding of how any such effect is partitioned among the various carbon stocks and flows (e.g. total plant biomass versus soil organic matter, gross photosynthesis versus gross respiration; etc.), which will give insight into the mechanisms leading to such an effect, and the conditions under which they prevail. (3) A combined empirical/mechanistic model to predict the effect of a given amount of warming on the basic carbon dynamics of our system, based on such input variables as microclimate, air temperature, and plant cover.

Approach: The study site is an ungrazed montane meadow at the Rocky Mountain Biological Laboratory (RMBL), Gunnison County, Colorado (38°53'N, 107°02'W, elevation, 2920 m). The basic experimental design consists of ten 3 x 10 meter plots laid out side-by-side along a north-south line (see Figure 1A). Each plot is on an incline, and is divided into two main zones: a drier upper zone and a lower one (see Figure 1B) in which moister conditions prevail because

it lies roughly a meter above a willow swale that is wet throughout most of the summer. The focus of our work is on the upper zone, which is more representative, in terms of vegetation and microclimate, of the subalpine ecosystems of the Rocky Mountain west.

The treatment (infrared radiation, IR) is assigned to alternate plots to facilitate the statistical isolation of treatment-control differences from north-south gradient effects. This treatment (a nearly uniform heat flux of about 22 W per square meter) is supplied by 1.6 m long electric heaters which are suspended 2.5 m above the ground. The heaters were first turned on in January 1991, and (apart from occasional malfunctions) have been in continuous operation since then.

Whole-system net CO₂ flux (net ecosystem production – i.e. gross photosynthesis, plant respiration, and soil microbial respiration) is measured in real time with a 75 cm x 75 cm square clear chamber attached to an infra-red gas analyzer system manufactured by Licor, Inc. which is placed over the center of each plot for about 60 seconds. Whole-system gross respiration is estimated by taking a similar measurement with a black box placed over the chamber to eliminate light and thus, photosynthesis. A smaller soil respiration chamber (7.5 cm diameter) is placed over patches of bare ground between plants to measure soil respiration (from plant roots and microbes). All carbon flux measurements are taken over a 24-hour cycle approximately once every ten days throughout the active growing season (June -August).

Carbon stocks in standing aboveground biomass are also measured at the same time as each carbon flux measurement (Harte and Shaw 1995), and soil carbon stocks (roots and soil organic matter separately) are sampled at the beginning and end of the growing season in representative soil cores taken from each plot. The organic matter content of the oven-dried, 2 mm-sieved soil was measured by loss of weight

on combustion.

Other measurements relevant to understanding carbon dynamics are also taken, including soil moisture and temperature (every two hours at 5 cm, 12 cm, and 25 cm depths), whole-system evapotranspiration rates, microbial biomass, nitrogen stocks in soil and vegetation, gross and net soil nitrogen transformation rates (mineralization, nitrification, immobilization), and C:N ratios in soil and plant biomass.

Results to Date:

Soil Microclimate: The principal direct effect of the heaters is to warm and dry the soil: the drier upper zone of our plots averages about 1.5 degrees C warmer in the heated plots during the growing season; soil water content as a percent of soil dry weight is typically 2 to 5% lower in heated plots, but can be zero or reach 10% or more, depending on conditions (there appears to be little or no effect at moisture extremes, and maximum effect at intermediate moisture levels). These microclimate results have potentially important implications for the carbon cycle. For example, the fact that soil drying (which, e.g., suppresses microbial activity) will accompany warming (which stimulates it), even in the absence of significant precipitation changes due to global warming, poses a potentially confounding factor for the widespread assumption (Kirschbaum 1995, Townsend, et. al. 1992, Raich and Schlesinger 1992) that soils will lose carbon with global warming because warmer temperatures cause an increase in heterotrophic respiration in the soil.

Carbon Fluxes: In the summer of 1993, daily-average whole-system carbon fluxes were measured approximately once every 10 days beginning on June 22 and extending through September. Integrating the difference in carbon uptake between heated and control plots over this time period (depicted in Figure 2) indicated that about 130 ± 80 grams less carbon meter⁻² was stored in the heated plots of the dry zone between days 170 and 270.

This sequence of measurements was repeated under the auspices of NIGEC funding in the summer of 1994, and was extended to include early-season effects (when *greater* carbon uptake would be expected in the heated plots due to earlier snowmelt), as well as measurements which enabled partitioning of

whole-system carbon-flux into various components. With the early-season effect included, there does not appear from the preliminary analysis to be a statistically significant difference in net carbon uptake in 1994 when integrated over the full growing season (see Figure 3), although there may be statistically significant early season effects and mid-to-late season effects which are in opposite directions (e.g., see days 135-160 versus days 170-200). This may indicate that the observed effect on carbon uptake in 1993 was the result of neglecting early-season growth in the heated plots; it is also possible, however, that since the summer of 1994 was extremely dry, the treatment effect on carbon uptake (which would be present under a more typical moisture regime) was suppressed (as was overall net system carbon-uptake, as can be seen by comparing Figures 2 and 3). The soil carbon data (see below) appears to support this latter interpretation.

The time-evolution of the treatment effect on soil respiration carbon fluxes is shown in Figure 4. As with the whole-system flux, there appears to be opposite effects at different times of the growing season: early in the season, when the soil is still wet from snowmelt, warming enhances soil respiration and heated plot soils lose more carbon (see days 150-160), but later in the season, when the soils are drier, heated plot drying suppresses respiration, and heated plot soils lose less carbon (days 170-180). On balance, the integrated 1994 soil respiration may actually have been slightly greater from control plots, but this difference does not appear to be statistically significant.

Soil Carbon Stocks: The stock of carbon in form of soil organic matter represents an integrated measure of carbon inflows and outflows to soil over past years, and thus gives a different perspective than that represented by the instantaneous flows. Figure 5 shows the data on soil carbon stocks for three dates. Measurements in June 1994 showed significantly less organic carbon stored in the top 15 centimeters of soil in heated plots relative to controls. By the end of summer 1994 (during which the control plot soils may, as indicated above, lost more carbon), the difference did not show up as significant.

The June 1994 difference in the stock of soil carbon indicates that, on balance, heated plots must have lost carbon relative to the controls —

Figure 1. Experimental Design.

A. Arrangement of warming plots along ridgeline. B. Typical heated plot profile (not to scale); temperature and moisture probe depths and locations are indicated.

Figure 2. Net Whole-System Carbon Flux, 1993

Figure 3. Net Whole-System Carbon Flux, 1994

Figure 4. Heated Plot Soil Carbon Gain (relative to controls), 1994

Based on Heated minus Control soil respiration (flux from atmosphere into ecosystem defined as positive). Error bars are 95% confidence intervals.

Figure 5. Soil Organic Matter Stocks (first 15 cm of soil)

Error bars are 95% confidence intervals

primarily due, we hypothesize, due to a decrease in photosynthetic production brought on by increased drought stress. This soil carbon data supports the interpretation above that the integrated 1994 flux measurements are anomalous in not showing a treatment effect, possibly due to extremely low growing-season precipitation.

We plan to pursue this work further by measuring 1995 litter production and decomposition, characterizing the soil carbon dynamics in greater detail (i.e. by dividing soil organic matter into rapid, slow, and intermediate turnover-time pools), continuing flux measurements in summer of 1995 (which, as of this writing, looks as though it will be a much wetter year), and using the resulting data to complete development of a statistical/mechanistic model of the carbon dynamics of our system.

Student participation: Doctoral students: Scott Saleska, Rebecca Shaw, Karin Shen. Masters Student: Andrew Wilcox. Undergraduates: Jen Hazen (Middlebury College), Sheridan Pauker (Harvard University).

Publications:

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Development of Field Instrumentation for Atmospheric Oxygen Measurements

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Objectives: The purpose of this project is to develop instrumentation for conducting continuous or semi-continuous measurements of atmospheric oxygen concentration at field stations. Such instrumentation would allow the collection of more detailed time series for atmospheric oxygen than is currently possible with flask measurement programs. One application of such detailed time series, for example, is to characterize year-to-year variations in the amplitude and shape of the oxygen seasonal cycle, which could provide a window into large-scale interannual variations in the ocean carbon cycle. A side benefit of this effort would be to create instrumentation that could analyze oxygen in smaller air samples than is possible with the interferometric analyzer which we currently employ for our flask program, thus reducing the cost of flask programs.

Products: We have fabricated a proto-type ultra-violet (UV) oxygen detector. We expect this work to lead to submission of a paper describing the UV method.

Approach: Most of our effort has focused on developing an oxygen sensor based on absorption of 147nm (UV) radiation emitted by a Xe resonance lamp. The method concept employs short-path absorption by oxygen in flowing (~20 sccm) air samples at reduced pressure (~100 torr). By using sapphire windows and CsI vacuum photodiodes as detectors, the detected light is effectively limited to the single 147nm emission line. The cell operates in an optically deep mode, with typically 90% of the incident light absorbed in the cell and only 10% transmitted. Under these conditions, a change of 0.0002 (2 ppm) in the oxygen mole fraction leads to approximately a 20 ppm change in transmitted light intensity. A high level of pressure stability is required in the absorption cell to reduce fluctuations in transmitted intensity simply related to variations in total pressure. The strategy involves switching rapidly between sample and reference gas upstream of the pressure control circuitry, in order to cancel long-term drift.

Recently, we have also been investigating the

use of a commercially available paramagnetic instrument (Columbus Instruments) which, in conjunction with a proper gas handling system, may be suitable for certain field applications.

Results to Date: Our first step in developing the UV instrument was to test a gas switching system with active pressure control. We had little difficulty achieving ppm-level stability with rapid (2-5 second) switching as required. We then interfaced this switching manifold to a single-beam UV optical cell using a commercially available DC discharge Xe lamp (EG&G) as the light source. We found that the plasma in this lamp is highly unstable under the specified operating conditions, and this effectively limited the precision of the oxygen measurement to the level of about 30 ppm in the mole fraction on short time scales. We tested driving the lamp in a pulsed mode, and this improved the stability of the lamp, but the precision was still limited to about 10 ppm on 1 minute time scales.

To reduce the effect of these lamp fluctuations, we then fabricated a cell that allowed a dual-beam arrangement, where the second beam monitors fluctuations in lamp intensity. Tests on this system using the pulsed lamp, and differencing circuitry, achieved a precision of around 2 ppm over minute long integrations. Although this is adequate for many applications, our aim was to produce an instrument with about an order of magnitude higher precision, which we believe is possible.

We then began investigating filling our own lamps using different pressures and mixtures of Xe with He or Ne, to reduce lamp intensity fluctuations. To investigate different lamp fills it was necessary to build a clean turbo-pumped high-vacuum system, and this has only recently been completed. We have found that mixtures of Xe and He yield a highly stable plasma and have fabricated two such lamps. We are just now beginning to test these lamps in the dual-beam cell, but no results are yet available to report.

The prospects for further refinement of the ultraviolet method seem very high. More work is

needed to investigate optimal lamp fills and to verify that these newer lamps have adequate lifetime. We also need to improve the detector electrometer circuitry, which is not yet optimized.

Our parallel effort on the paramagnetic instrument, which we have obtained on loan, has focused on operating the instrument at steady flows of about 200 sccm at elevated pressures. We have found that the instrument is quite sensitive to temperature fluctuations as well as to mechanical vibration. Nevertheless, we have verified that the raw sensitivity of the instrument

operated at several bar is at the ppm level, although the instrument output exhibits irregular drift, typically at the rate of several ppm per minute. We are investigating the feasibility of canceling this drift by improving the temperature control of the unit and by switching rapidly back and forth between sample and reference gases.

Student participation: The work on the paramagnetic instrument has been conducted by Andrew Manning, a second-year Ph.D student at Scripps. He has worked half-time on this project since June 1995.

Exploring Use of Cosmogenic ^{10}Be and ^{36}Cl As Tools for Delineating Extreme Natural Prehistoric Variability in the Polar Stratosphere, Related to Volcanic Aerosols, Cl and O_3 Chemical Reactions

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Objectives and Approach: This progress report covers the work done during this two-year research project. The central aim of the project was to find out why the relative fall-out of two cosmogenic nuclides, ^{10}Be and ^{36}Cl in the polar ice is very variable, and furthermore, why the absolute fall-out of ^{36}Cl is about an order of magnitude higher than that expected from its cosmic ray production (Elmore et al, 1987; Finkel et al, 1980; Lal and Peters, 1967). To some, it appeared that the anomaly lies in the fall-out of ^{36}Cl , and not with ^{10}Be whose fall-out seems to be well understood in terms of its cosmic ray production. After a detailed examination of the various potential mechanisms involved in the observed patterns in the fall-out of ^{10}Be and ^{36}Cl , we concluded that most probably this was due to the dominating influence of certain stratospheric chemical reactions as observed recently in the polar stratosphere in complex homogeneous and heterogeneous reactions involving Cl-species in the polar stratospheric clouds. Consequently, it was decided to go into details of the various mechanisms that may give rise to the anomalous fall-out of ^{36}Cl with respect to ^{10}Be in the polar regions. A multi-pronged attack was therefore planned on this problem which is indeed a most formidable one compared to any confronted so far in studies of the global production and fall-out

of cosmogenic nuclides.

Results to Date and Work in Progress: As a result of our theoretical calculations (to be published) and model simulations, we can now assert that no unknown sources of ^{36}Cl exist, and that in the pre-nuclear weapon era, the natural fall-out of ^{36}Cl should primarily be cosmogenic. Maximum contributions from the accretion of cosmic dust, the nuclear activation of Cl in the stratosphere by the reaction, $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$, etc., are all estimated to be insufficient by at least two to three orders of magnitude.

Simulation studies rule out the possibility of any scenario of appreciable changes in the stratosphere-troposphere mixing which could lead to an excess fall-out of ^{36}Cl in the polar regions, without a corresponding change in the fall-out of ^{10}Be .

A possibility not completely ruled out at present is that the ^{36}Cl production rate in the atmosphere has been grossly underestimated by us! Our experience in this field makes this possibility most unlikely. However, to give this doubt a chance, we are now measuring by a direct method the cosmogenic production rate of ^{36}Cl in the atmosphere. This is being done by exposing

argon to cosmic radiation at a high altitude so that the ^{36}Cl produced in cosmic ray nuclear reactions with argon can be measured even in a relatively short exposure. We have recently exposed eight high-pressure argon cylinders at Mt. Evans (14,000 ft a.s.l.). Some of these cylinders will be analyzed for cosmogenic ^{36}Cl after one year (1995), and the rest after two years (1996), using the accelerator mass spectrometry (AMS) technique at Purdue University.

In addition to our direct measurements of ^{36}Cl by cosmic radiation, we had planned to also make some measurements of ^{36}Cl formation cross-sections in irradiation of argon with 30-60 MeV neutrons at the UC Davis Crocker National Laboratory. This should provide a supplementary check on ^{36}Cl production rates since the energy spectrum of cosmic ray neutrons in the atmosphere is fairly well known. However, it was not possible to undertake this program for numerous reasons.

We are also emphasizing on understanding the various mechanisms by which Cl can be removed from the atmosphere in rain-out processes, specifically mechanisms that favor removal of Cl nuclei over Be nuclei, which are expected to exist primarily as attached to atmospheric aerosols and are expected to follow the well-known pattern for removal of aerosols from the atmosphere. This is a complex subject, but we are hopeful for some breakthroughs.

More recently, several measurements have been made of fall-out of ^{36}Cl and ^{10}Be in wet

precipitations (Knies et al, 1994). Combining our studies with these invaluable data, we are quite hopeful that we will be able to either understand the problem, or at least put sufficient constraints on different scenarios presently being considered as the cause of the anomaly in the ^{36}Cl fall-out. At present, it does appear that the final answer would be closely related to complex chemical reactions that occur in the cold environment of the polar stratosphere.

Products: A number of papers are in preparation on the sources of production (and injection) of ^{36}Cl in the atmosphere, and possible chemical reactions that can alter the relative ^{36}Cl to ^{10}Be concentrations in fall-out. The work on production of ^{36}Cl in argon exposed to cosmic rays is ongoing and will take about one year to complete.

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Sink-Source Characteristics of Two Distinctly Different Forest Species and Riparian Species as Affected by Elevated Carbon Dioxide and Soil Moisture

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Objectives: Assessment of the impact of projected global climate change conditions on the sink-source relationships and their regulatory processes in representative species of two distinctly different ecological systems. Elevated atmospheric carbon dioxide has been documented to initially enhance net carbon assimilation and increase whole plant growth rates. However, photosynthetic processes can acclimate to increased CO₂. Acclimation may occur due to the modulation of sink strength in various tissues over the long-term. The combined influences of elevated CO₂ and soil moisture on the assimilation and deployment of carbon into plant structure is integrated through stomatal and non-stomatal limitation.

The objectives of this study are to evaluate the long-term influences of combined soil moisture status and elevated carbon dioxide on the carbon assimilation. We are specifically addressing carbon allocation (partitioning into foliage, stems and roots) and the regulatory processes controlling these sink-source relationships in two distinctly different leaf strategies (needle versus broad-leaf).

Products: (1) Increased understanding of the integration of mechanistic controls that regulate plant growth response to these climate change variables in ecologically and economically important long-lived forest species. (2) Identification and characterization of enzymatic processes controlling increased biomass (carbon) accumulation. (3) Development of a function balance growth model with predictive value and generalized application.

Approach: We are assessing a conceptual control model as regulating process of carbon assimilation and transpirational water flow. This control model is a self-integrating series of feedback loops with varying sensitivities environmental variables. The salient points of this coordination process are: 1) stomatal and

non-stomatal limitations to carbon gain and water-loss, 2) biochemical limitations, changes in carboxylation, internal carbon allocation and transport, 3) structural responses in plant growth form resulting from differential carbon partitioning which affects light interception and below ground resource acquisition (water and nutrient gain).

These studies are being conducted in eight controlled environmental chambers with phenological day/night temperatures. The tree species being studied are *Pinus ponderosa*, *Platanus racemosa* (two-year seedlings) and *Taxus brevifolia* (three and four-year old seedlings). The two conifer species are receiving sub-canopy irradiance levels of 600 $\mu\text{mol s}^{-1} \text{m}^2$, while the riparian species receives 1000-1100 $\mu\text{mol s}^{-1} \text{m}^2$ at canopy height. All chambers CO₂ levels are continuously monitored and adjusted by a dedicated time shared infra-red gas analyzer and data acquisition system. Two of the environmental chambers are maintained at 350 $\mu\text{L L}^{-1}$ CO₂, three chambers each at 525 and 700 $\mu\text{L L}^{-1}$ CO₂. All trees are potted in 18 L pots containing native soils from their respective ecosystems. Soil moisture is maintained by a drip irrigation system and monitored by time domain reflectometry (TDR) at levels of -0.3 to -0.6 MPa, -1.0 to -1.3 MPa and -2.0 to -2.5 MPa.

The variables that are being measured are growth (stem caliper and height), leaf gas exchange (A , g_s , C_i , E , CE), photochemical properties (F_v/F_m , chlorophyll content), biochemical activities and content (Rubisco, SPS, SS and AI), carbohydrate contents (starch, glucose, fructose, etc.), leaf properties (LA, SLM, internal anatomy (e.g., vascular and mesophyll content)), and carbon allocation (biomass, and partitioning into leaves, stems and roots).

Results to Date: Growth measurements were used to calculate relative rates of caliper incrementation and stem elongation. The three

species all exhibited increased growth (caliper and stem elongation) after one year exposure to increased atmospheric CO₂. Sycamores (*Platanus racemosa*) exhibited the least incrementation of stem caliper (25% between 350 and 700 $\mu\text{L L}^{-1}$ CO₂) but showed a stem elongation of 44% at the same CO₂ levels. *Pinus ponderosa* increased stem caliper by 30% but only increased stem length by 18% when grown at 700 $\mu\text{L L}^{-1}$ CO₂. Pacific Yew (*Taxus brevifolia*) demonstrated the greatest growth enhancement, 42% increase of stem caliper and a 60% increase in stem length. The yew's increased growth parameters were achieved at 525 $\mu\text{L L}^{-1}$ CO₂ with little or no additional enhancement at 700 $\mu\text{L L}^{-1}$ CO₂. In Ponderosa pine (the only completed harvest to date) no significant changes in biomass or root/shoot ratios were observed as a function of CO₂.

Contrasting strategies in individual tree canopy deployment has been observed. Total leaf area in Ponderosa pine seedling decreased by 10% and 37% at 525 and 700 $\mu\text{L L}^{-1}$ CO₂ exposure respectively. This decrease in canopy area was a result of the dropping of older age class needles. Limited data on canopy area of the yew is available but it appears to be increased with a high retention of all age class needles. Sycamores appear to increase the photosynthetic surface area by maintaining leaf number, leaf dimensions and increased retention of leaves. Leaf retention was determined from litter fall data and exhibiting a decrease with increasing CO₂ levels.

Changes in needle anatomy and morphology were observed in both of the pine and yew, while the sycamore data is preliminary it appears that no significant alterations have occurred. SLM increased significantly and could only partially be accounted for by increases in leaf starch content with increased CO₂ exposure. While no significance was found in needle cross-sectional area there was a trend toward longer needles with decreased mesophyll content and increased vascular content.

Carbon assimilation rates on a leaf area basis were significantly influenced by elevated CO₂ exposure in both Ponderosa pine and sycamore, while the yew maintained relatively stable values at all growth levels. The pines exhibited a 39%, and 53% increase in A at 525 and 700 $\mu\text{L L}^{-1}$ CO₂ exposure respectively when compare with A at 350 $\mu\text{L L}^{-1}$ CO₂. Stomatal conductance (g_s)

did not exhibit any significant changes between treatment levels. C_i values increased with treatment level but C_i/C_a remained constant at approximately 0.64. Soil moisture had small effects on both A and g_s. The Pacific yew maintained a relatively stable A m⁻², while significantly reducing g_s thereby holding C_i at approximately 280 $\mu\text{L L}^{-1}$ CO₂. The broad-leaved sycamores showed a decrease in A m⁻², g_s was significantly decreased with increasing CO₂ and C_i remained around 244 $\mu\text{L L}^{-1}$ CO₂. These data strongly suggest that metabolic feedback mechanisms are acting to coordinate source activity with sink demand.

A/C_i curves used to calculate CE in Ponderosa pine showed that a 33% increase at 700 $\mu\text{L L}^{-1}$ CO₂ compare with the other two treatment levels of CO₂. *In vitro* biochemical assessments of Rubisco confirmed increases in the activation state and total activity at the highest CO₂ exposure. These data suggest that the Rubisco content had changed on per unit area basis but that increased C_i had increased its activation state. Sucrose-phosphate synthase (SPS) specific activity exhibited a significant increase at the highest CO₂ exposure (62%). Immunoblot analysis has suggested that this increased activity is due higher specific protein content. Data on enzymatic processes of both *Taxus brevifolia* and *Platanus racemosa* are current being conducted.

These data are being integrated in a functional balance growth model. This model will address carbon allocation at balance point between shoot and root limitations on growth rate.

Publications:

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Presentations:

Effects of elevated carbon dioxide on growth and physiology of Ponderosa pine. Presented at the First International Conference for Global Change and Terrestrial Ecosystems (GCTE). Woods Hole, MA. June 1994. Presented by J.C.Pushnik.

The long-term exposure to elevated carbon dioxide on a canopy dominant species: *Pinus ponderosa*. Presented at the American Society of Plant Physiology. Portland OR. July 1994 by S. Bauer and J. C. Pushnik.

The effects of long-term exposure to elevated carbon dioxide of a Sierra-Nevadan dominant species: *Pinus ponderosa*. Presented at the 16th International Conference of the International Union of Forestry Research Organizations (IUFRO) Fredricton NB Canada by J.C. Pushnik.

The effects of elevated carbon dioxide on the enzymatic activity of sucrose-phosphate synthase in *Ponderosa pine*. Presented at the 27th Air Pollution Workshop Cuernavaca Mexico by S. Bauer (funded by DOE/EPA student travel grant).

Physiological response of *Pinus ponderosa* to prolonged exposure to increased CO₂; curious physiological adaptations. J. C. Pushnik (Invited Speaker) Department of Biology, New Mexico State University, Las Cruces NM, May 1995.

Variability in the intraspecific response of *Pinus ponderosa* seedlings subjected to long-term exposure to elevated CO₂. Presented at 88th Air Waste Management Association Meeting San Antonio, TX, June 1995 by James L. J. Houpis (travel funded by DOE).

Student participation: Graduate Students (Master's): Scott M. Bauer 50%; William Flory 25%; Rene Smith 50%, Debbi Stolp 25%. Undergraduate (Research Credit): Javier Alcazer 25%, Derek Blattler 25%, Daniel Englehart 50%, Shawnia Forester 15%, David Garcia 15%, Matthew Goehring 15%, Jonathan Leavenworth 10%, Mark Takegaki 50%, Mike Lennox 15%.

Sensitivity of Tundra Methane Emissions to Water Table Level: Field Manipulation Experiments at Permanent Sites

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Objectives: This project involves water table manipulation experiments aimed at determining the sensitivity of tundra methane and carbon dioxide fluxes to changes in water table. The objectives are (1) to design, build and field test an experimental pumping system suitable for performing water table level manipulation experiments on meter-scale sites, and (2) to employ this system in well-understood wetland

sites to determine the sensitivity of methane and carbon dioxide emissions in natural systems to changes in water table level.

Products: The products of this study will be a reliable battery-operated system suitable for field manipulations of water table level, information on the sensitivity of methane and carbon dioxide emissions to water table level in manipulated

sites, and better information on control mechanisms need for modeling.

Approach: Our approach is to partially isolate experimental sites from the adjacent soil water regime by placing sheet aluminum collars into the soil. The collars are 1 m on a side, and extend below the surface to just above the maximum thaw depth (40-50 cm). The collars serve as cofferdams and restrict lateral groundwater flow. A well for removal or addition of soil water is located in the center of each collar. Soil water is pumped from one collar into an adjacent collar, allowing flux measurements under raised and lowered water table conditions. They enclose an area large enough to accommodate several of the flux chambers we have used in previous work.

Aluminum water table manipulation collars (1 m x 1 m) are driven into a slot cut with a chain saw around the perimeter of the collar. The collars are set to a depth close to the maximum thaw depth, usually 40 cm or more. A well bored in the center of each collar is cased with a screen-covered 4" diameter perforated PVC pipe. The pumping and control system employs a small (3.8 cm diameter x 16.6 cm long) high pumping capacity (18 liters per minute) 12 v submersible pump (Amazon model LVM 105). The pump is controlled by two float-actuated magnetic reed switches (Omega LV-60). The system employs a latching relay that allows the pump to operate between the switch limits; the pump operates until the lower switch is actuated and resumes operation only when the upper switch is actuated. The pumping system is powered by a deep-cycle storage battery, which is charged by a photovoltaic module (Solarex MSX-10 lite). The pump and float switches are mounted on an angle iron, which is suspended at an appropriate depth in the central well. Water table level within the experimental collars is measured by determining the water level in perforated 1" PVC pipes. The pipes are fitted with a driving point to prevent plugging with soil during installation. Fluxes of methane and carbon dioxide are measured at two locations within each of the water table manipulation collars using flux collars and aluminum flux chambers (Whalen and Reeburgh, 1988, 1992).

Background: Microbially-mediated methane oxidation is a globally important process that is about 200 Tg yr⁻¹ larger than net emission to the atmosphere (Reeburgh et al., 1993). Methane

oxidation appears to be particularly important in modulating methane fluxes from wetland, tundra, and rice agricultural systems. Laboratory studies on tundra soil core segments (Whalen et al. (1995) indicate that lowering the water table level 10-20 cm can enhance methane oxidation to a point where it balances production, eliminating net methane flux to the atmosphere. Further decreases in water table level result in net oxidation of atmospheric methane, which has been observed in dryer soils. Carbon dioxide fluxes are expected to increase under lowered water table conditions; whether wetlands will become larger overall greenhouse gas sources remains a question. Field measurements in chronically drained forested bogs show low and zero methane fluxes at low water table levels (Lein et al., 1992; Roulet et al, 1993).

We lack a good process-level understanding of methane oxidation in tundra and wetland environments. Subsoil methane distributions and fluxes appear to be decoupled, as high standing stocks of soil methane and steep soil water gradients show poor correlations with surface fluxes (Whalen and Reeburgh, 1992). Correlations between methane fluxes and water table level in wetlands are generally poor, and appear to be masked in whole season correlations. The magnitude of methane standing stocks compared with the surface methane fluxes suggest residence times of days. However, laboratory water table manipulation experiments on peat cores give results that suggest much slower responses. The laboratory work of Moore and Roulet (1993), which involved measuring methane fluxes in packed peat columns under rising and falling water table showed very dissimilar methane fluxes under rising and falling water table, indicating response lags and suggesting that inundation history may be important. Similar studies in natural cores (Kizer et al., in preparation) showed that the methane fluxes of cores subjected to water table adjustments stabilized only after periods of weeks. Water table manipulations on meter-scale natural systems are needed to resolve the differences between laboratory and unmanipulated field studies, to provide information on response times of natural systems to seasonal water table changes, and information on the effect of inundation history.

Field Sites: We intended to conduct this experiment in the University of Alaska Arboretum in the vicinity of the permanent sites studied in

our previous flux time-series work (Whalen and Reeburgh, 1988, 1992). Four water table manipulation collars were installed in September, 1992, when thaw depth was maximum. Fairbanks experienced an unusually early snow in 1992, and when we resumed field work in May, 1993, it was clear that conditions were much dryer than usual. Very little water accumulated in the Arboretum site wells following the spring thaw. Further, silt layers deposited by previous floods within the soil column limited lateral hydraulic conductivity, and water table recovery following pumping was quite slow. The deep water table and slow well recovery, combined with lack of rainfall, cast doubt on our ability to conduct this experiment within the Arboretum. By mid-June 1993, all of the Arboretum wells were dry.

We relocated the experiment to a wetter site located within the Lemeta Bog, a short distance from the University of Alaska Fairbanks campus. The site we chose has remained wet through the previous two summers and consists of mosses with interspersed tussocks. Four water table manipulation collars and two pumping systems were installed in the Lemeta Bog on June 20. Flux chamber collars were installed and two sets of methane and carbon dioxide flux measurements were made prior to starting the pumps on July 2. Flux measurements were made at weekly intervals through mid-September. The performance of the pumping systems was excellent. The peat soils at the Lemeta Bog site have good lateral permeability, so we were able to uniformly lower the water table 5 to 10 cm within the pumped collars in a matter of two days. Conditions were unusually dry during the summer of 1993, and the water table within the Lemeta Bog dropped to the lowest levels observed in three years this site has been studied. Continuous pumping was needed to maintain an elevated water table level, so we elected to observe the system under naturally lowered water table conditions and made no further attempts to manipulate water table. Laboratory jar experiments were performed on Lemeta Bog soils to determine soil methane oxidation kinetic properties, the sensitivity of soil methane oxidation to changes in temperature and soil moisture, and the soil temperature and moisture optima.

1994 Field Work: The Lemeta Bog water table manipulations were resumed on June 22, 1994, and normal water table levels permitted lowering

of water table in two collars. Methane and carbon dioxide flux measurements were made at approximately 5 day intervals. It appears that inter-site variability, which is equivalent to that observed by Whalen and Reeburgh (1992), is equivalent to effects resulting from manipulation. A manuscript is in preparation. We also measured methane oxidation rates in jar incubations from Lemeta Bog cores and determined the moisture and temperature sensitivity of methane oxidation. We observed that soils adjacent the water table are the locus of most of the methane oxidation in these cores. Further, these soils were able to oxidize and produce methane without lag when incubation conditions were changed from oxic to anoxic. These results indicate that methane oxidation occurs in a thin "gauntlet" and that our notions about water table lowering having a cumulative effect should be reconsidered.

We established an additional site in a wet sedge meadow in the Toolik Lake LTER on August 1, 1994. This site is representative of large areas of coastal arctic tundra and is adjacent to other manipulation experiments involving shading, warming (greenhouses) and fertilization (N, P) conducted by LTER investigators. Four years of summer time series flux measurements are available for comparison. Attempts to establish additional sites were unsuccessful because of heavy rains and flooding in early September. We were able to maintain the water level 10 cm below the surroundings. Seasonally integrated fluxes for the collar with lowered water level were half that of collars with raised water tables.

We also developed a conductivity probe for determining water table levels in the water level wells. This portable battery-operated device is based on detecting a change in electrical conductivity when electrodes contact the water level. It consists of a MOSFET device which activates a LED when electrodes at the tip of a probe contact water. The sensor worked well during the 1995 field season, but we plan minor modifications (audible signal, more rigid probe) for future work.

1995 Field Work: Major effort was put into the Toolik Lake wet meadow sites. Five additional collars were installed, bringing the total to 7 in the wet meadow site. The water table manipulation experiment now consists of 1 unmanipulated control site, 2 sites with raised water tables, and four with lowered water tables.

Elevated walkways have been constructed to avoid disturbance during sampling and maintenance. Twice-weekly measurements of methane flux and net ecosystem exchange of carbon dioxide (NEE) were made at all sites. A LiCor model 6200 instrument was used in the NEE measurements. Large (1 m x 1 m) chamber tops were made of plexiglas and aluminum and mounted directly on the collar lips. These were operated along with the previously deployed small (25 cm x 25 cm) collars to assess within-collar spatial variability. High resolution depth profiles of methane were sampled using newly built equilibration samplers. These were also used to collect samples for methane stable isotope analysis. Emitted methane was collected late in the season for stable isotope analysis. We plan to use differences between the isotope ratio of below-ground and methane collected from chambers along with stable isotope fractionation factors to estimate the fraction of methane oxidized. The pump and control systems functioned well.

The 1995 field season was wetter and colder than 1994. The control sites remained inundated for most of the season. Integrated fluxes from the lowered water level collars were approximately the same as the raised water level

collars. Recent work by Happell et al. (1994) shows that floodwaters are the site of extensive methane oxidation. Analysis of the stable isotope samples mentioned above will clarify this point.

The Lemeta Bog sites experienced some minor vandalism during the winter of 1994-5. The sites were restored and were occupied, but at lower frequency than in previous years. We are collaborating with Dr. S. C. Tyler in construction of a low background oxidation line for preparation of methane samples for stable isotope analysis.

Presentations and Publications:

Reeburgh presented invited paper at 8th International Symposium on Microbial Growth on C-1 Compounds, 27 August - 1 September 1995, San Diego. Paper "Soft Spots" in the global methane budget", will appear in 1996 symposium volume.

Students participation: Two Ph.D. students, Shannon K. Regli (second year student supported by NSF OPP LALI) and Jennifer Y. King (first year student supported by NSF traineeship) have benefited from logistics and research support from this project.

The Role of the Ocean in Climate Variability: Ocean Ventilation Processes, Thermohaline Variability, and Feedbacks of the Ocean to the Ice and to the Atmosphere

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Objective: To identify and to understand (1) mechanisms of ocean internal variability on decadal to millennial time scales and (2) mechanisms of feedback of the ocean to the atmosphere and to the ice. The overall objective is to understand natural climate variability so as to better understand anthropogenically forced climate change.

Product: (1) understanding of oceanic ventilation and transport processes and variability, (2) comparison of solutions between an isopycnal and z-coordinate OGCMs in the

same global model geometry, with emphases on thermocline structure, meridional heat transport and thermohaline circulation, and (3) a coupled ocean-atmosphere model through coupling the National Center for Atmospheric Research Community Climate Model (CCM2) with OGCMs in various configurations.

Approach: Both isopycnal and z-coordinate coarse resolution OGCMs were used. The coupled model is obtained by coupling the CCM2 with OGCMs. Various idealizations based on observation were made in order to isolate the

essential physical processes in studying particular mechanisms.

The isopycnal global OGCM used is the one developed by Dingming Hu at NOAA/GFDL and at the JISAO. The model distinguishes itself from both Oberhuber's isopycnal model and the Miami Isopycnal Coordinate Ocean Model in that it can provide direct comparisons of the global isopycnal simulation with that of a level model for the same model parameters, geometry and boundary conditions over a wide range of temporal and spatial scales. The algorithm for computing diapycnal velocity is an improved version of the original one (Hu, 1991), and it has been implemented together with a realistic equation of state (Hu, 1995). The model has options of various diapycnal mixing parameterizations: constant, stability dependent (i.e., $\sim N^{-1}$) or Richardson number dependent vertical diffusivities. The B-grid finite difference scheme of the model is energy conserving with a generalized vertical coordinate, and it is well suited for applications that require resolving meso-scale eddies. Contrary to the rigid-lid GFDL model, Hu's model has a free surface, which allows the model to incorporate as many islands as the model resolution can resolve without significantly increasing computational cost. The model can be used with or without a Kraus-Turner mixed-layer model. In the later case, the isopycnal layers outcrop to the top model level of fixed depth. It is emphasized that the isopycnal model naturally contains the isopycnal layer-thickness diffusion parameterization of eddy induced tracer transports by Gent *et al.*, 1995. This allows easy comparisons of the isopycnal model with GFDL OGCM in the same parameter space when Gent *et al.* parameterization is used.

The z-coordinate OGCM used is the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM). The models use three configurations: (1) single hemisphere rectangular box, (2) two hemisphere rectangular box with a zonal reentry slot in the south, and (3) two hemisphere and two basin rectangular box with a zonal reentry slot in the south. Both restoring and mixed surface boundary conditions are used.

Results to Date: A coarse resolution (3° latitude by 4° longitude) run with the isopycnal model has been carried out. The model geometry, surface forcing, and horizontal resolution are identical to those in Danabasoglu *et al.* (1994, DMG

hereafter). The mixing parameter values are also chosen based on those used in DMG. The only differences are the values of lateral viscosity and layer- thickness diffusivity, which are respectively $109 \text{ cm}^2/\text{s}$ and $2 \times 10^7 \text{ cm}^2/\text{s}$ in the isopycnal model, compared to $1010 \text{ cm}^2/\text{s}$ and $107 \text{ cm}^2/\text{s}$ in DMG. Spun up from the Levitus climatological annual-mean temperature and salinity, the model has been integrated for 1600 years and has virtually reached an equilibrium state. Fig. 1 shows the zonal and annual mean potential temperature derived from the Levitus data, the isopycnal model, the standard GFDL MOM (HOR) and DMG. The isopycnal model gives better representation of the bowl like structure in the northern subtropics. The deep ocean is warmer in HOR, colder in DMG than observed, while the deep ocean in the isopycnal model is in better agreement with the observations. Fig. 2 shows the annually and globally averaged vertical profiles of potential temperature from the observation of Levitus and Boyer (1994) and from the isopycnal model simulation: the agreement is nearly perfect. This is the first time that an ocean model simulated a sharper main thermocline than the observed one in the global average even though the model simulation is not tuned for the best results. Fig. 3 shows annual mean northward heat transports. The maximum of the northward heat transport in the isopycnal model is about 1.27 PW , larger than 1.2 PW of DMG.

A simulation of sea level variations of the world oceans has also been carried out, in a collaborative work with Yi Chao at the JPL of Cal Tech. The model has a horizontal resolution of 1° latitude by 2° longitude and a realistic bottom topography. The isopycnal model was spun up from the Levitus January climatology with the Hellerman and Rosenstein climatological monthly-mean surface wind stress and relaxation to the Levitus monthly-mean surface temperature and salinity. After 10 years of spin up, the surface forcing of the model was switched to wind stress, heat and fresh water fluxes derived from the NMC data from Jan., 1992- Sept., 1993. The model is able to simulate annual-mean and seasonal variations of sea-level observed from TOPEX/POSEIDON and seasonal variations of the equatorial current system. Even though the model resolution is not fine enough to resolve the equatorial instability waves, the spring-time zonal flow reversal in the eastern equatorial pacific is well produced (Fig. 4).

A coupled atmosphere-ocean model has been developed by coupling the NCAR CCM2 with OGCMs for various configurations. We are carrying out experiments with the coupled model to study feedbacks of the ocean internal variability to the ice and to the atmosphere and to study how ocean and the atmosphere partitioning heat and moisture transports in determining the climate. Results will be reported in the next progress report.

Because coupled model studies demand large computational resources, we are also carrying out sensitivity studies of ocean model in trying to understand coupling of interdecadal to millennial thermohaline oscillations and to understand ventilation processes in the circumpolar ocean. In previous work, we have analyzed interdecadal thermohaline oscillations in an OGCM and have proposed mechanisms for these oscillations (Yin and Sarachik, 1995a; Yin, 1995). Understanding of these modes of variability is important for climate prediction since the state of the art coupled ocean-atmosphere models have similar thermohaline modes. We have continued the investigation of thermohaline oscillations from decadal to millennial time scales and associated coupling. We found that these oscillations on different time scales can coexist, and they are inherently coupled together in releasing heat to the atmosphere. A detailed analysis is reported in a manuscript in preparation (Yin and Sarachik, 1995b).

Coupled ocean-atmosphere model experiments with transiently increasing CO₂ show that there are cooling and long delayed warming in the southern ocean, which suggests that ventilation processes associated with the formation of intermediate and bottom waters and with the inherent circumpolar ocean dynamics play an important role in sea surface temperature (SST). We have undertaken a thorough examination of these ventilation processes with coarse resolution OGCMs. It is found that intermediate water formation is an intrinsic feature of the circumpolar ocean dynamics, and the upwelling in the southern ocean plays an important role in SST. We also found that the mid-depth southward flow in the south Pacific depends crucially on the bottom water formation rate in the Pacific, and its existence is a result of continuity and circumpolar ocean dynamics. Since this mid-depth flow upwells to the surface in the southern ocean, it plays an important role in variability of SST and surface ¹⁴C

concentration. Detailed results will be presented in a manuscript in preparation (Yin and Sarachik, 1995c).

An analysis of proposed mechanisms for climate variability is performed in a set of lectures given at a NATO Advanced Study Institute (Sarachik, Winton and Yin, 1995). External forcing variability, coupled modes, internal ocean variability, ENSO variability, and random variability are all covered.

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Fig. 1 Zonal and annual mean potential temperature derived from a) the Levitus data (after DMG, 1994), b) the isopycnal model run at year 1600, c) HOR of DMG and d) ISO of DMG.

Fig. 2 Annually and globally averaged vertical profiles of potential temperature from the observations of Levitus and Boyer (1994) and from the isopycnal model simulation.

Fig. 3 Northward heat transport in all oceans for a) the isopycnal model run, at year 1600, b) HOR and ISO of DMG. The maximum northward heat transport in the isopycnal model is 1.27 PW, larger than 1.2 PW in ISO of DMG.

Fig. 4 Seasonal variations of the simulated surface zonal current on the equator in the Pacific Ocean during Sept. 1992 - Sept. 1993. The model is able to simulate the spring-time zonal flow reversal in the eastern equatorial Pacific though the model resolution is not fine enough to resolve the equatorial instability waves.

Global Systems Science: An Interdisciplinary Course for High School Students

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Objectives:

- Prepare national trial editions of six of the nine Global Systems Science Student Guides.
- Prepare Teacher Guides and evaluation forms for each of these guides.
- Establish additional linkages with laboratories currently conducting studies in global environmental change so as to enrich and update the instructional materials.
- Test the student materials in classrooms with different student populations scattered across the country.
- Combine the results of classroom testing with suggestions from scientists to produce revised editions of the Global Systems Science course materials.

Products: Last year we completed the first two Student Guides:

Changing Climate
Life and Climate

This year we have completed six additional Student Guides. These include:

Global Systems Science, an Introduction
Closing the Ozone Hole
Losing Biodiversity
Energy Flow
Energy Use
Human Population Impact

We have also prepared a draft of the last guide in the series:

Ecosystem Change

For each of these six guides we also prepared Teacher's Guides, with suggestions for presenting the materials, and additional activities and resources. We also prepared evaluation sheets for classroom testing for each chapter of each guide, and drafts of materials for teachers to use in assessing student performance.

Approach: An essential complement to the grants received from WESTGEC to develop the GSS high school program has been a grant from the National Science Foundation Teacher

Enhancement Division that has enabled us to bring 125 high school teachers to Berkeley to assist in the development and dissemination of the GSS materials. These teachers have pilot tested the GSS materials in their classrooms, and will assist in the classroom impact study that will take place with during the 1995-96 performance period.

So far, 103 teachers in 37 states were involved in testing these guides with their students. More than 3,000 high school students, mostly in grades 9 and 10, were involved in these trials. Classroom testing involved the following steps:

- a. We notified teachers that volunteers were needed to test these materials in their classrooms during the 1994-95 school year. This was done through a newsletter published by the Climate Protection Institute, by announcements in publications of state science teacher associations and by direct contact with former participants in Global Systems Science summer institutes. More teachers responded than were needed. 48 teachers were involved in these trials, testing *Losing Biodiversity*, *Closing the Ozone Hole*, *Human Population Impact*, and *GSS An Introduction*. These trials occurred during January, February, and March, 1995.
- b. A brochure describing the two NSF funded institutes was produced and distributed. Notices of these institutes were also published in the newsletter of the Climate Protection Institute and in publications of the National Science Teachers Association. From the more than 300 applicants 55 were chosen. These teachers tested *Energy Flow*, *Energy Use*, and *Losing Biodiversity* in their classrooms during April, May, and June of 1995.
- c. All trial test teachers were provided with 30 copies of the guide(s) that they had agreed to test, and evaluation forms for each chapter. Teachers in the first group sent in

their evaluations by mail. Teachers in the second group are reporting on the results of their trials at the GSS Institute in Berkeley during July and August, 1995.

As each guide is revised, we will send it to two leading scientists in appropriate fields as a final check for accuracy, and to be certain we have not left out vital information.

Results to Date: Although the trial test teachers have provided us with many specific suggestions for improving the materials, the overwhelming consensus is that the materials were very well received by the students. Reading levels were about right, the concepts were important and within the grasp of most students, and the motivation to learn the material was high because the students found the subjects very interesting, and relevant to their concerns.

In addition to classroom trials of the Student Guides, two teachers from Lowell High School in San Francisco have agreed to pilot test some of the evaluation instruments that will be used in the Fall to assess the impact of the GSS program on high school students. The teachers have been provided with classroom sets of four of the Student Guides and the associated Teacher Guides. They will be using these materials for the summer school programs they are conducting for entering freshman at Lowell High School in September of 1995.

During the 1994-95 year we consulted with the following scientists, so as to incorporate their research and perspectives into the GSS materials:

Ashok Gadgil, science and economics of energy conservation, Lawrence Berkeley National Laboratory, Berkeley, California

Byron Wood, mitigating human disease by use of remote sensing images, NASA Ames Research Center, Moffitt Field, California

Christopher Potter, seasonal changes in carbon dioxide levels in the atmosphere, NASA Ames Research Center, Moffitt Field, California

Dixon Stroup, energy transport in the ocean system, atmosphere-ocean interactions, University of Hawaii, Manoa Campus, Honolulu, Hawaii

Estelle Condon, overview of research mission and projects of the Earth Science Division, NASA Ames Research Center, Moffitt Field, California

Hector D'Antoni, remote sensing and paleoclimatology, NASA Ames Research Center, Moffitt Field, California

Jay Skiles, plant response to changing levels of carbon dioxide, NASA Ames Research Center, Moffitt Field, California

Joe Jordan, stratospheric ozone studies, NASA Ames Research Center, Moffitt Field, California

Joseph Boyle, comparison of global climate models worldwide, Lawrence Livermore National Laboratory

Kurt Kreith, mathematics of population growth, University of California, Davis, California

Lynn Talley, role of the ocean in climate change, Scripps Institute of Oceanography, La Jolla, California

Stephen Klooster, seasonal changes in carbon dioxide levels in the atmosphere, NASA Ames Research Center, Moffitt Field, California

Samira Omar, desert ecology, Kuwait Institute for Scientific Research, Kuwait, and University of California at Berkeley

We have featured the work of many individual scientists and technicians as career role models in the Student Guides, including photographs of the individuals and descriptions of their backgrounds and current research.

Publications: During the next year we will begin the search for a commercial publisher of the GSS course materials. Ideally we would like to publish the student material in three forms: as a set of nine inexpensive paper-back booklets, as a single hard bound book, and as a CD ROM. We would like to produce the Teacher's Guides for all volumes as a single loose-leaf notebook. We anticipate publishing the results of the impact study that we will conduct next year in a refereed journal such as *Science Education*.

An Investigation of Atmosphere-Land Interactions Under Arctic Conditions

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Objectives: The surface energy balance of the arctic landscape, including the flows of radiant, sensible and latent heat between the land and the air, depends upon the amount and phase of water at or near the surface. Biogeochemical cycling of nutrients, and the processes that control the emission or uptake of greenhouse gases, are controlled by the water cycle and surface energy balance. The hydrological processes of the polar regions, however, are inherently different from those in more temperate latitudes: most of the water exists in solid form (ice) during a large portion of the hydrological cycle. Snow covers the landscape dominates the regimes of lakes, rivers and the active layer. The existence of permafrost affects the transfer of liquid water, gases, and water-borne materials within the arctic terrestrial system and from the land to the ocean.

The objective of this study was to develop a coupled atmosphere-land surface-permafrost model to improve our physical understanding of the transfer of momentum, heat, and water between the atmosphere and the land in arctic regions.

Products: A coupled atmosphere-land surface-permafrost model has been developed. The coupled model consists of the following submodels: (i) atmospheric radiative transfer submodel; (ii) surface turbulent flux submodel; (iii) soil temperature (including the active layer and permafrost) submodel; (iv) soil moisture submodel; and (v) seasonal snow cover submodel.

Approach: The coupled model includes resolution of the vertical profiles of temperature and moisture content from deep within the permafrost through the active layer, seasonal snow cover to the atmosphere through the surface energy and mass balance.

Atmospheric radiative transfer: A comprehensive atmospheric radiative transfer model developed by Tsay et al. (1989) based upon the discrete ordinate method of Stamnes et al. (1988) is applied to calculate the surface

radiative energy fluxes. The model utilizes a high-order discrete-ordinate approximation to solve the radiative transfer equation (Stamnes et al., 1988) for both solar and terrestrial spectra and has detailed routines for including the effects of clouds, arctic haze, greenhouse gases and snow layers under arctic conditions. The atmosphere is divided into a sufficient number of layers to adequately resolve physical and optical properties. The input parameters required for the radiative transfer model include atmospheric pressure, temperature, and moisture profiles. These profiles are derived by averaging sounding data for every month for the period from 1980 through 1991 at Barrow for tundra and McGrath for boreal forest conditions, respectively.

Turbulent transfer: The near-surface turbulent transfer is calculated using bulk aerodynamic formulae. The bulk formulae do not explicitly model the intermittent turbulence that may occur in a very stable atmospheric boundary layer which is common at high latitudes. Effects of the stable atmospheric boundary layer is approximated by using a stability-dependent transfer coefficient (Louis, 1979).

Soil temperature: Soil temperatures are calculated using a one-dimensional finite element heat transfer model with freezing and thawing in soils and permafrost containing unfrozen water and with temperature dependent thermal properties. Latent heat effects are incorporated into an apparent heat capacity. The soil is divided into 35 layers with the lower boundary at 30 m which is deep enough to ensure no significant effect on temperature at shallow depths and with a constant heat flux lower boundary condition. Thermal and physical properties of the soil in any single layer are constant but are allowed to vary from one layer to another. Physical and thermal properties of soils are obtained from Osterkamp (1987) and Zhang (1989, 1993).

Soil moisture: Soil moisture is calculated using the Darcian equation for one-dimensional fluid flow for the same soil layers as for the thermal regime. Water vapor and liquid water movement

in response to temperature gradients are ignored. Drainage from layers cease when the soil temperature is at or below its freezing point. The hydraulic conductivity and the soil water suction profiles are related to the average soil volumetric liquid water content and a soil texture parameter "b" by power relations presented in Clapp and Horberger (1978). The surface liquid moisture content, which is required to evaluate the surface soil water suction and the surface albedo, is obtained through the surface mass balance equation.

Seasonal snow cover: When the snow thickness is less than 5 cm, the seasonal snow cover is treated as fresh and/or new snow modeled as an additional variable depth "soil" layer, using the same equations for heat fluxes and the surface energy balance as in the soil temperature submodel. When the snow thickness is greater than 5 cm, the snow cover is divided into three layers: fresh (new) snow, wind slab and depth hoar layer. Thickness of the fresh snow (the top layer) is fixed at 5 cm, while the thickness of the wind slab and depth hoar layer changes with the total thickness of the seasonal snow cover. At present, the depth fraction of the depth hoar layer (ratio of thickness of depth hoar layer vs. thickness of the total snow cover) varied from 0.3 to 0.6. Physical and thermal properties of each layer are constant with time. The snowmelt is modeled using a detailed surface energy balance evaluation.

At each time step, the surface temperature and soil layer temperatures and liquid and frozen moisture contents are first retrieved from memory. Then, the surface radiative fluxes and turbulent fluxes are calculated and substituted into surface energy and mass balance equations to re-evaluate the surface (snow or soil) and soil temperatures and moisture profiles for the next time step.

Results to Date: Development, validation and coupling of several submodels into a comprehensive model is a very time consuming process and the two reviewers of this research proposal pointed out that this study would require a multiyear effort. After completion of the coupled model, we mainly focused upon investigation of the interactions of clouds, seasonal snow cover, surface radiative fluxes, and the ground thermal regime at high latitudes. Some of the primary results are as follows:

(i) Under cloudy conditions, the total downward solar radiation is greater with snow-covered surface than with bare-soil surface. This is due to the impact of high reflectivity on snow surface and multiple scattering between clouds and snow surface.

(ii) Atmospheric moisture (both water vapor and liquid water) is the single most important factor influencing the incoming longwave radiation to the surface.

(iii) the surface cloud-radiative forcing is positive for most of the year except during the period from July to the middle of August, hence clouds at high latitudes tend to warm the lower atmosphere and the surface from late August through June and to cool the lower atmosphere and surface from July to the middle of August.

(iv) Atmospheric thickness defined as the vertical distance between 500 mb and 1000 mb pressure surfaces, can be used as an indicator to predict the large scale snowmelt at high latitudes. Atmospheric thickness of 5250 m at Barrow and 5200 m at McGrath is sufficient to trigger snowmelt.

(v) The depth hoar layer of the seasonal snow cover is one of the most important factors influencing the insulation effect of snow cover at high latitudes. Modeling results show that for the same snow thickness, depth fraction of the depth hoar layer along the Arctic Coast is about 0.30, while inland, the depth fraction increases to more than 0.50.

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Student Participation: Xu Jierong, 50%.

Holocene ^{13}C , Climate and Carbon Cycling: Information from Macrofossils and Sediments of a Pacific Northwest Lake

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Objectives: The objectives of this study are to provide estimates of atmospheric $\delta^{13}\text{C}$ levels and paleo-humidity of southeastern Vancouver Island from late glacial times to the present and to determine how carbon cycling within a small lake changes with changing climate.

In C-3 plants the ratio of stomatal conductance to assimilation rate in plants is proportional to the relative humidity through a wide range of temperatures, CO_2 pressures, and photon flux densities (Ball, 1988; Collatz et al., 1991). Ignoring dark respiration and photorespiration, $\delta^{13}\text{C}$ in terrestrial plant material can be directly related to atmospheric $\delta^{13}\text{C}$, and inversely related to humidity and stomatal conductance (White et al, 1994). The $\delta^{13}\text{C}$ of the plant material, combined with an estimate of the change in atmospheric $\delta^{13}\text{C}$ from ice cores (Leuenberger et al., 1992), can be used to calculate the change in relative humidity from plant material preserved in lake sediment, provided stomatal conductance has not changed or can be estimated from stomatal density differences in fossil and modern leaves. Alternatively, if two different $\delta^{13}\text{C}$ datasets are available the change in relative humidity and in $\delta^{13}\text{C}$ of the atmosphere can be calculated.

$\delta^{13}\text{C}$ in plant cellulose may be affected by

physiological factors such as age of the plant and local nutrient stress, as well as humidity. Pollen deposited in the lake sediments is derived from numerous trees over a wide geographic range. To complement the measurements being made on cones and twigs, we will use $\delta^{13}\text{C}$ of pollen extracted from the sediment.

Because many factors influence the $^{13}\text{C}/^{12}\text{C}$ ratio of bulk organic lacustrine matter, the record of $\delta^{13}\text{C}$, % carbon, and C/N versus depth is most valuable as a study in the changes in carbon cycling with changing climate. A comparison of the deep and shallow water sediment $\delta^{13}\text{C}$ is useful for interpreting changes in the total $\delta^{13}\text{C}$.

Products: 1) A well-dated record of $\delta^{13}\text{C}$ in lacustrine organic matter and terrestrial material (pollen, cones, wood) found in the sediments of Heal Lake, Vancouver Island, Canada, spanning the last 13,000 years. 2) Estimation of changes in paleo-relative humidity and atmospheric $\delta^{13}\text{C}$ from $\delta^{13}\text{C}$ of cones and pollen. 3) Study of the effect of climate change on carbon cycling in the deep and shallow water sediments. 4) Support of the hypothesis that a climatic event occurred in the Pacific Northwest around the time of the Younger Dryas interval in the North Atlantic region

Approach: $\delta^{13}\text{C}$ measurements are made on pretreated cones and twigs obtained from the sediments and from modern trees in the area. The average $\delta^{13}\text{C}$ value of the modern cones, the modern average growing season relative humidity, and the global atmospheric $\delta^{13}\text{C}$ value are used to calculate the stomatal conductance for the species in question. The measured $\delta^{13}\text{C}$ of the cones and twigs from various depths in the sediments can then be used to calculate changes in relative humidity from the present. Measurements of stomatal density on modern and sediment extracted lodgepole pine needles can be made to constrain the influence of stomatal conductance changes. Correlation of relative humidity estimates with fire frequency information derived from charcoal analysis of the sediments from the late glacial interval will provide a useful check on the method.

The highest purity pollen samples obtained from the sediments using the method developed by Brown (1994) contain about 78% pollen and 22% plant fragments by simple counting. $\delta^{13}\text{C}$ was measured on extractions of various purities (15-78%) to determine the effect of the plant fragment contamination. There was little correlation between amount of plant fragments and $\delta^{13}\text{C}$ indicating, at least for the one depth tested so far, that the plant fragments do not significantly alter the $\delta^{13}\text{C}$ signal. Pollen is being extracted from several sediment depths corresponding to periods of relatively stable climate to test the method before applying it to the periods of interest such as the glacial/Holocene transition.

$\delta^{13}\text{C}$, percent carbon, and in some cases C/N, were measured on total organic carbon after pretreatment to remove carbonates, and in most cases, sieving at 425μ to remove larger debris. Because Heal Lake was drained before we began sampling, no comparison of $\delta^{13}\text{C}$ of modern dissolved organic carbon (DIC) and surface sediment could be made. Three lakes of similar size in the area have been sampled for DIC, surface sediment, and plankton $\delta^{13}\text{C}$ measurements for comparison.

Results to Date: From the lodgepole pine cone samples analyzed so far, relative humidity appears to have been about 20% lower around 11,700 ^{14}C yrs BP rising to near modern levels around 11,650 ^{14}C yrs BP until it dropped back to about 20% below modern around 11,000 ^{14}C yrs BP (Fig. 1). Samples used for this

calculation are mostly from a high sedimentation section spanning from the glacial clay at the base of the lake to a colluvium deposit dated at $10,900 \pm 30$ ^{14}C yr BP. The date for the colluvium layer deposition was made on a sample of about forty lodgepole pine cones resting on the sediment just below the colluvium. Ages for samples from this and other sections are currently estimated by linear interpolation between radiocarbon ages. AMS measurements for about twenty samples are planned and a model for the calibrated sample ages will be developed. If stomatal density, and hence stomatal conductance, was higher during the time of lower atmospheric CO_2 pressure, as was the case for limber pine needles analyzed by Van de Water et al. (1994) the estimated change in relative humidity would be greater.

The transition from late glacial to the Holocene climate is recorded as a 1.5 - 2.0‰ increase in $\delta^{13}\text{C}$ of organic carbon from shallow and deep water sediments (Fig. 2, crosses and triangles, respectively). This transition is only partially accounted for by the increased lacustrine productivity evident from a delayed increase in percent carbon and a decrease in the C/N ratio from around 25 to 15 (not shown). Before the Holocene transition the deep water sediments are enriched by about 2.5‰ relative to the shallow sediments. This difference decreases to about 1.8‰ after the transition. Warmer temperatures, combined with a drop in lake level around this time, may have caused an increase in methanogenesis resulting in a lighter CO_2 component. A 1.54‰ drop in $\delta^{13}\text{C}$ coincident with an abrupt decline in percent carbon, found only in the deep water sediments, is consistent with the timing of the deposition of the colluvium layer around the lake margin at beginning of the Younger Dryas. Age estimates are from linear interpolations of three radiocarbon dates of bulk gyttja for both cores and are subject to revision with further dating. Those on the deep water core were obtained by Dr. Richard Hebda of the University of Victoria in conjunction with palynological work.

Publications:

Reimer, P.J., 1994, Carbon isotopes in macrofossils and sediments from a Pacific Northwest Lake, 15th International Radiocarbon Conference Abstracts, Glasgow, Scotland, 15019 August, 1994, p. PE-20.

Presentations:

Carbon isotopes in macrofossils and sediments from a Pacific Northwest lake,
15th International Radiocarbon Conference,
Glasgow, Scotland, August, 1994.

A Younger Dryas-like climatic event in the Pacific Northwest, Geological Association of America, October, 1994.

Student participation: Paula Reimer 100%;
Christine Williams 50%.

Figure 1. The calculated change in relative humidity from the modern value based on $\delta^{13}\text{C}$ measurements in lodgepole pine cones. Age estimates are based on a bulk gyttja sample taken just above the basal clay and a sample of about forty lodgepole pine cones from the top layer of gyttja below the colluvium deposit.

Figure 2. $\delta^{13}\text{C}$ and percent carbon for shallow water sediments (crosses) and deep water sediments (triangles). Lines are three point moving averages.

Fig. 2

Objective Deduction of the Spatial and Temporal Distribution of the Methane Sources

Ka Kit Tung and Margaret K.M. Brown
University of Washington

Objectives: An objective estimate of the spatial and temporal distribution of the individual methane sources. An objective estimate of the errors in the estimated methane source distribution. An assessment of the information content in the available geographical, observational, and isotopic methane source data.

Product: A general algorithm for the determination of the surface sources of atmospheric trace gases to be used with 2 or 3 dimensional chemical transport models.

Approach: The temporal and spatial distribution of the methane sources is determined using an objective inversion algorithm and a 2-dimensional chemical transport model. Using the Singular Value Decomposition, we systematically identify those components of the global methane budget which are well defined by observations of atmospheric methane at the Earth's surface. We then use the Singular Value Decomposition to identify independent information, taken from geographical and isotopic studies, capable of constraining those components of the global methane emissions that are poorly defined by the observations of atmospheric methane.

Results to Date: The $\delta^{13}\text{C}$ of methane is a measure of the ratio of methane containing the carbon isotope ^{13}C to methane containing ^{12}C . This quantity is thought to have utility in constraining the magnitude of the individual methane sources because of the distinct isotopic signatures associated with each source. For example, bacterially produced methane is generally depleted in the ^{13}C isotope with mean values of $\delta^{13}\text{C} \cong -60 \pm 5\text{‰}$, relative to non-bacterial methane with mean values of $\delta^{13}\text{C}$ ranging from $\cong -41 \pm 8\text{‰}$ to $-27 \pm 3\text{‰}$. Therefore, the $\delta^{13}\text{C}$ observed in the atmosphere will be a result of the mixing of methane from these sources and will contain information on the relative fluxes of each source. Knowledge of the $\delta^{13}\text{C}$ of the methane emissions within some region will constrain the magnitude of the individual methane sources within that region. However, for these constraints to be useful the uncertainty in the estimated isotopic ratio of the

total methane emissions within a region must be small relative to the range in the isotopic signatures of the individual methane sources within that region. For example, if the $\delta^{13}\text{C}$ of methane emissions within a region is known within an uncertainty of $\pm 10\text{‰}$ then it may be possible to distinguish the relative fluxes of the individual methane sources with isotopic signatures that differ by greater than this amount and conversely, it will be impossible to distinguish the contributions of the individual methane sources with isotopic signatures that differ by less than this amount. For atmospheric methane the individual methane sources have isotopic signatures ranging from about -32‰ for methane produced by biomass burning to about -86‰ for methane produced by peat bogs. This relatively small range in isotopic signature constrains the acceptable uncertainty in the deduced isotopic composition of methane emission to be at the most 10‰ .

Our earlier finding shows that the currently network of sites which collect $\delta^{13}\text{C}$ of atmospheric methane is not adequate in discriminating individual sources of methane. The question is, if we have a much denser $\delta^{13}\text{C}$ observational network, as proposed by some groups, can the uncertainty in the inverse problem be improved so that useful information can be extracted from the isotopic measurement? Using hypothetical (dense) observational networks, we showed that, given the uncertainty in the estimate of (total) methane emission, improving the spatial density of the $\delta^{13}\text{C}$ observational network with the intention of reducing this uncertainty will be ineffective. Specifically, the singular value decomposition analysis of this hypothetical inverse isotopic ratio problem shows that the sensitivity of the most significant components of the solution are not improved and that the information contained in the data set is not significantly improved. This uncertainty is dominated by the uncertainty in the methane emissions estimate. From these results we conclude that the most effective way for reducing the uncertainty in the $\delta^{13}\text{C}$ of the methane emissions will be to first reduce the uncertainty in the estimated distribution of (total)

methane emissions.

Publications:

Brown, Margaret K.M., 1995: The Singular Value Decomposition Method Applied to the Deduction of the Emissions and the Isotopic Composition of Atmospheric Methane, *Journal of Geophysical Research*, (In press).

Manuscripts in preparation and submitted:

Brown, Margaret K.M. and Tung, K.K.: The evolution of the vertical distribution of atmospheric source gases: Implications for the initialization of chemical transport models.

Student participation: Ming Fang: 17%.

Comparisons of Observed and Model Cloudiness and Model Climate Sensitivity

Bryan C. Weare
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Objectives: The overall goal of this project is to both identify which models best represent observed variations in cloudiness and to indicate how agreement or lack of agreement with observations is likely to be related to model sensitivity to climatic forcing. This goal involves two basic steps.

(A) Observations of monthly mean cloudiness and its variability will systematically be compared with most of the world's current climate models. Those models will then be ranked according to their ability to match the observed statistics. (B) The climate sensitivity of the observed atmosphere and models in terms of the net solar and infrared heating at the surface and top of the atmosphere will be calculated and related to changes in cloudiness in order to both better understand the relevant processes and to identify the best available models.

Products: The original proposal outlined the following products. (1) An assessment based upon satellite and other cloud observations of the modes of intra- and interannual variation. (2) An assessment of the modes of intra- and interannual variation of cloudiness in climate model simulations. (3) An assessment based upon observations of the relationships between variations in the solar cloud radiative forcing at the surface and top of atmosphere and variations in cloudiness and other meteorological variables. (4) An assessment of the relationships between solar and infrared cloud radiative forcing and cloudiness in climate model simulations. (5) A

monthly mean estimate of cloudiness as a function of height from the observed cloud data using the procedure summarized in the original proposal. (6) An assessment of the similarities and differences between observed and modeled three-dimensional cloud fields with those of the net radiation budgets at the top and bottom of the atmosphere.

Approach: The cloud observations are drawn primarily from those of the International Satellite Cloud Climatology (ISCCP), which are currently available for July 1983 through December 1990. Statistics include monthly and daily estimates of cloud amount, cloud top pressure and cloud water content.

The climate models utilized are the large number of models taking part in DOE funded Atmospheric Model Intercomparison Project (AMIP). This project includes all of the major climate models with nearly all present-day cloud formation mechanisms. All of these models have been run for a standard ten-year period, January 1979 through December 1988, with identical observed sea surface temperature (SST) and sea ice boundary conditions. Available from AMIP are total cloud amount and the net solar and infrared radiation at both the top and bottom of the atmosphere as well as the SST forcing condition. Other potentially useful addition variables are also available. The principle investigator is the head of a AMIP diagnostics subproject and thus has complete access to the current and future output statistics and the

software developed by AMIP to access and plot these statistics.

Results to Date: Excellent progress has been made on a wide range of objectives. This includes:

(1) Total cloud amounts for the results for the twenty-nine AMIP models have been obtained, analyzed, and compared with the ISCCP, Nimbus-7 and Meteor satellite observations. The comparisons include annual global, zonal and regional means and root-mean-square differences. In addition smoothed seasonal cycles, which were calculated based upon the two most important empirical orthogonal functions of the individual monthly means, are being compared to comparable observations. Results for twenty-five models were presented at a NATO Advanced Research Workshop in July 1994 (Weare et al., 1995a). In addition results related to how well models simulate total cloudiness changes during the 1982/83 and 1986/87 El Niño/Southern Oscillation (ENSO) events were presented at TOGA 95 (Weare, 1995a). The summary paper covering the results for all twenty-nine models is scheduled to be published in September 1995 (Weare et al., 1995b). The basic conclusion of this paper that few of the models clearly reproduce either the spatial variations of the annual mean or seasonal variations reflected in the observations.

(2) Zonally averaged cloudiness as a function of pressure level in twenty-four AMIP models has been analyzed. In order to allow comparison with satellite and surface observations of high and low cloud amounts, the model data have been transformed using adjustments for differing emissivities (opacities) of the high clouds and a 'random overlap' assumption. The latter accounts for the fact that, for instance, the low cloud observed from a satellite is obscured by middle and high cloud. Preliminary results of this analysis were presented at the NATO workshop (Weare et al., 1995a) and a recent AMIP research conference (Weare, 1995b). The final results recently have been submitted to the *Journal of Climate* (Weare, 1995c).

(3) Preliminary analyses of estimates of the observed degree of cloud overlap throughout the globe are being completed. This work, which involves an analysis of both satellite observations of high, middle and low clouds and surface observations of low clouds, was temporarily

slowed because the most readily available analyses of cloudiness made by surface observers either did not include low cloud amounts or did not overlap with the satellite observations. This required deriving from the raw marine observations monthly estimates of low and total cloud cover for the 1980's. This has now been completed.

(4) Strong steps to continue useful collaboration with AMIP Subproject Co-investigator Dr. Igor Mokhov of the Russian Academy of Science were made through further personal contact at the NATO Workshop and the recent AMIP research conference.

(5) Monthly means of total solar and infrared fluxes at the top of the atmosphere for both cloudy and clear subregions have been analyzed from the Earth Radiation Budget Satellite (ERBS) for January 1985 - December 1988. A soon-to-be-published paper (Weare, 1995d) show that these ERBS clear-sky infrared fluxes are likely to be contaminated by undetected clouds giving rise to uncertainties of up to about 10Wm^{-2} . This is shown to have a substantial impact on the greenhouse forcing of the atmosphere.

Student participation: Tomoniro Watanabe, M.S. Student, UC Davis, 50%, ~\$25,000; David Pyles, Ph.D. Student, UC Davis, 50%, ~\$17,000.

Publications:

Weare, B. C., T. Watanabe, and I. Mokhov, 1995a: Variations of cloudiness and its variability in global climate models. In *Proceeding of the NATO Workshop on Climate Sensitivity to Radiative Perturbations: Physical Mechanisms and Validation*. (In press.)

Weare, B.C., I.I. Mokhov, and AMIP Modeling Groups, 1995b: Evaluation of total cloudiness and its variability in the Atmospheric Model Intercomparison Project. *J. Cli.* 8, (In press).

Weare, B.C., 1995a: Evaluation of Cloudiness in the AMIP during ENSO. In *Proceedings of the TOGA 95 International Conference*. (In press.)

Weare, B.C., 1995b: Evaluation of Cloudiness and its Variability in the Atmospheric Model Intercomparison Project. In *Proceeding of the AMIP International Conference*. (In press.)

Weare B. C., 1995c: Factors controlling ERBE long-wave clear-sky and cloud forcing fluxes. *J. Cli.* (In press).

Weare, B.C., 1995d: Evaluation of the Vertical Structure of Zonally Averaged Cloudiness and its Variability in the Atmospheric Model Intercomparison Project. *J. Climate*. Submitted.

Progress Reports Not Received Due To Late Funding

Dr. Anthony Fisher, U.C. Berkeley, Global warming and carbon dioxide

Progress Reports Not Yet Received

Dr. Steve Koonin, Cal Tech, Earthshine measurements of the global albedo

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