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GLOBAL CLIMATE FEEDBACKS: CONCLUSIONS AND RECOMMENDATIONS OF THE JUNE 1990 BNL WORKSHOP

Bernard Manowitz

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ENVIRONMENTAL CHEMISTRY DIVISION
DEPARTMENT OF APPLIED SCIENCE
BROOKHAVEN NATIONAL LABORATORY
UPTON, NY 11973

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FOREWORD

These conclusions and recommendations are the cooperative output of three panels from a larger group of scientists who met at Brookhaven National Laboratory on June 3-6, 1990, to attend a workshop on Global Climate Feedbacks. The scientific presentations described in the appended Table of Contents will be published shortly, along with these conclusions and recommendations. This document is being made available to the attendees and to the sponsors of the workshop for review and comments.

The panels consisted of the following:

Panel on Atmospheric Feedbacks

R. Cess (SUNY), V. Ramanathan (U. Chi.), D. Randall (CSU),
J.P. Blanchet (CCC), S. Schwartz (BNL), A. Heymsfield (NCAR),
M. MacCracken (LLNL), M. Wesely (ANL), P. Michael (BNL),
L. Newman (BNL), G. Stokes (PNL), P. Mutchlecner (LASL)

Panel on Ocean Interactions and Sea Ice Response

K. Bryan (GFDL/NOAA), E. Boyle (MIT), J. Sarmiento (Princeton),
D. Wallace (BNL), P. Falkowski (BNL), J. Downing (PNL),
W. Hibler (Dartmouth), R. Moritz (U. Wisc.), M. Bender (U.R.I.)

Panel on Land Surface Feedbacks

W. Emanuel (ORNL), D. Schimel (CSU), J. Hobbe (MBL),
G. Hendrey (BNL), F. Bazzaz (Harvard), M. Post (ORNL)

I am indebted to Avril Woodhead, Kathy Vivirito, Steve Schwartz, Paul Falkowski, George Hendrey, and Mikc MacCracken for assisting in editorial reviews of this document, to Claire Lamberti and the DAS Administrative Support Group for preparing the manuscript, and to Richie Tulipano for preparing the cover. Steve Schneider was instrumental in helping plan the workshop and Flo O'Brien was of invaluable aid in making the arrangements. The workshop was sponsored by the Atmospheric and Climate Research Division of the Office of Health and Environmental Research (DOE).

B. Manowitz
Workshop Chairman

GLOBAL CLIMATE FEEDBACKS: PROCEEDINGS OF THE WORKSHOP AT BROOKHAVEN NATIONAL LABORATORY - JUNE 3-6, 1990

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GLOBAL CLIMATE FEEDBACKS: CONCLUSIONS AND RECOMMENDATIONS OF THE JUNE 1990 BNL WORKSHOP

The issue of global change initiated by increases in the concentrations of CO_2 and other greenhouse gases is a scientific issue with major policy implications. The best means to examine the response of the Earth's climate to prospective perturbations in radiative forcing caused by such changes, and to other industrial activities, is modeling, specifically by means of general circulation models (GCMs) of the Earth's atmosphere and of the coupled atmosphere-ocean system. However, for these models to be useful, it is imperative that they accurately represent all the significant responses of the climate system to changes in forcings, not just direct responses, but also indirect responses, i.e., feedbacks. Because some of these feedbacks are not represented in the models, or are inaccurately represented, the models will yield descriptions of the response of the climate system to perturbations that are erroneous in magnitude, and perhaps, even in sign.

At the most simplistic level, these feedbacks will alter the response of global mean temperature to a specific change in forcing. However, as discussed at the workshop, responses of the Earth's climate to a change in forcing are much more varied than can be captured in a single variable such as global mean temperature, encompassing changes in the cloud amount, cloud vertical and horizontal distribution, and cloud microphysical properties; the amount and pattern of precipitation; the snow and ice cover of land; the amount and distribution of sea ice; the atmospheric and ocean circulations patterns; the amount, type, and distribution of surface vegetation; photosynthesis and respiration rates. All of these changes will alter the response of the Earth's climate system to any primary changes in forcing from that caused only by the primary change in forcing.

The purpose of this workshop was to identify the feedbacks inherent in the Earth's climate that actually or potentially govern the system's response to perturbations, to identify gaps in knowledge that preclude the accurate representation of these feedbacks in models, and to identify research required to represent these feedbacks accurately in models.

The feedback processes are essentially a response to a perturbation. The reference perturbation for the workshop assumed an increase in the atmospheric concentration of greenhouse gases. If we assume a doubling of the CO_2 equivalent gases, the forcing function will amount to about 4 W m^{-2}.

The most significant readjustment to the perturbation is the increase in the amount of atmospheric water vapor. Further readjustments could occur due to changes in cloud, rainfall, and snow patterns, as well as increases in oceanic evaporation and terrestrial evapotranspiration. Rising temperatures may alter the ratio of plant respiration to photosynthesis; rising CO_2 levels directly affect plant productivity as well. The responses of the vegetation can alter terrestrial carbon storage, leading to further shifts in atmospheric gas concentrations. Sea ice can be transported from one region to another, with melting and freezing occurring at different locations. Such transport tends to create net imbalances in salt fluxes in the ocean. Resulting changes in ocean thermohaline circulation can themselves initiate climatic changes. Climatic changes, including not only temperature changes but also changes in precipitation/evaporation and wind regimes, will undoubtedly affect physical and biogeochemical processes in the upper ocean layers and hence affect the dynamics of air-sea CO_2 exchange processes.

Of the many feedback processes that were discussed, all phases of water were identified as being the most important contributors to moderating or amplifying climate perturbations that might be initiated by increased atmospheric trace gases.

The major conclusion of the workshop on feedbacks was that the only feedback where sign and amplitude is confidently known is that of water vapor; specifically, water vapor provides a positive amplification of the temperature change after a heating perturbation by a factor of ~1.6. At present, there is no confidence in the sign of the feedbacks associated with changes in cloud cover and cloud properties, ocean sources and sinks of CO_2, changes in surface hydrology (including vegetation transpiration, and albedo, changes in land surfaces, and changes in sea ice cover); snow feedback is almost certainly positive, but the magnitude of the feedback is unknown.

However, within the next decade, the international program, and particularly the U.S. program as described in the Committee on Earth Sciences (CES) document "Our Changing Planet - The FY 1991 Research Plan of the U.S. Global Change Research Program,"* should provide more definitive values for feedbacks and materially reduce the present uncertainties.

The individual workshop panels made several recommendations on research to accelerate the needed reduction of feedback uncertainties, and indicated how the recommended research can be coordinated with the CES plan.
The recommendations are given in priority order.

REPORT AND RECOMMENDATIONS OF THE PANEL ON ATMOSPHERIC FEEDBACKS

The amount of an increase in the greenhouse effect due to CO_2 will be enhanced by increased concentrations of water vapor, with the magnitude of the change depending on the extent of temperature rise, because water vapor is itself strongly controlled by surface temperature through the Clausius-Clapeyron equation. Other feedbacks involving water occur through clouds, surface hydrology, sea ice, and snow. Magnitudes and signs of these feedbacks are not certain; snow feedback is almost certainly positive. Surface hydrology includes considerations of changes in albedo and evapotranspiration. The sea ice feedback is especially uncertain because as sea ice retreats, and sea-surface albedo decreases, it seems to give rise to low, highly reflective stratus clouds.

The panel recommended several field research projects and model intercomparisons that would enhance our ability to describe these feedbacks. The intercomparisons would also provide necessary (though insufficient) tests of the accuracy

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*This document may be obtained from the Committee on Earth Sciences, c/o U.S. Geological Survey, 104 National Center, Reston, VA 22092.

of the treatment of these feedbacks in the models, thereby lending enhanced confidence in the use of these models to address "what-if" questions pertinent to the future climate. Emphasis was placed on projects that could realistically be undertaken on a time-scale of five years or less. The following classes of research projects based on field measurements were recommended:

1. It is widely expected that the EOS program will be the primary satellite observation program. An important pre-EOS activity is the Earth Probes program that will place smaller, specialized platforms in orbit up to six years earlier than the projected 1998 first launch of an EOS satellite. The first ARM site will be operational in 1992, with others following in subsequent years. Thus, there will be no overlap with at least the first ARM site for about six years. Therefore, ARM satellite observations will have to rely on other satellites for a significant part of the ARM program as presently planned.

The panel recommended that a coordinated measurement program be initiated to simultaneously observe atmospheric radiation at the surface, at the tropopause, and at the top of the atmosphere. ARM sites would be suitable for surface measurements. Top-of-troposphere measurements might be made with an unmanned aircraft platform; it is understood that DOE is evaluating use of such platforms in ARM. Short- and long-wave radiation should be measured ideally using instruments (closely modeled after the ERBE scanners).

Much discussion was devoted to the need for high quality calibrated satellite measurements of top-of-the-atmosphere radiation with broad-band high spatial resolution scanners. These needs include: (1) establishing continuity between ERBE and CERES/EOS; the ERBE satellite failed early in 1990; the CERES/EOS is not scheduled to be on line until 1998 at the earliest, but may well be delayed based on experience with earlier large NASA projects; continuity is required to search for greenhouse warming signals in the radiation budget; (2) extension of measurements used by Raval and Ramanathan,* in both clear and cloudy regions; (3) determination of absolute shortwave flux to the surface as input to ocean models and coupled ocean-atmosphere models; (4) correlation of satellite measurements with ARM sites to establish the ability of ARM sites to serve as ground truth locations for the satellite measurements, and to complement radiation measurements at the surface and top of the troposphere; and (5) definition of aspects of later EOS flights, particularly to serve as prototype and test-bed cases for the scanners to be used on CERES.

The choice of a low polar orbit appears best for making most of the measurements and has the advantage of giving global coverage with a frequent revisit time. However, observing the development of convective activity would also be very useful, but would require a geosynchronous orbit which would not give a global view. Both objectives could be met with multiple satellites. It may be useful to explore international cooperation to meet the needs of the coordinated measurement program in the nineties. The desirable measurement capabilities for the satellite are as follows:

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*Raval and Ramanathan, Observational determination of the greenhouse effect, Nature 342, 14 December 1989, 758-761.

Parameter	Desired
Water Vapor Profile	
0-10 Km	
accuracy	±20%
vertical resolution	2 Km
horizontal resolution	2.5°x2.5°
10-30 Km	
accuracy	±50%
vertical resolution	2 Km
horizontal resolution	2.5°x2.5°
Temperature Profile	
accuracy	0.5K
range	0-15 Km
vertical resolution	5 Km
horizontal resolution	2.5°x2.5°
Clouds	
cover	2%
top height	±0.25 Km
emission temperature	±0.5K
albedo	±0.01
water current	±0.5 Kg/m^2
Radiation Flux	
short-wave acc.	2%
long-wave acc.	2%
long + short acc.	2%
Aerosols	
accuracy	5%
vertical resolution	1 Km
horizontal resolution	2.5°x2.5°
Planetary Boundary Layer	
height	±0.05 Km
horizontal resolution	50 Km

The acquisition of even a portion of these measurements equivalent to ERBE data would be very valuable if obtained simultaneously with ARM measurements.

2. The workshop endorses the Global Energy and Water Cycle Experiment (GEWEX; NSF/NOAA/NASA/DOI). The scientific objectives of GEWEX include describing and understanding the transport of water (vapor, liquid, and solid) and energy in the global atmosphere and at the underlying surface, and developing methods of predicting changes in the distribution of water within the global atmosphere and on the underlying surface, which may occur naturally or through

human activities. However, only modest support is scheduled to be provided in FY 1991 for planning and development activities in preparation for GEWEX field projects, process studies, and modeling research. The workshop recommends an enhancement of the GEWEX field program, possibly by coordination with DOE's ARM program on measurements of water (all phases) as function of position (3-dimensional); these measurements are especially important in the upper troposphere, where water vapor forcing of cirrus is the key to accurate understanding of cirrus forcing. Present knowledge above 500 mb is especially poor. Rawindsondes are notoriously unreliable at the low concentrations of water vapor characteristic of these altitudes. The recommended time-scales are temporal: resolution from daily to monthly-mean for extended periods.

3. The CES report states that NSF, NOAA, DOE, and DOD will provide support for and conduct investigations of the chemical transformations and modeling studies that determine the fate of natural sulfur emissions. The emphasis will be twofold: (i) fundamental laboratory characterization of the sequential transformation of the sulfur compounds, and (ii) testing the laboratory data against field observations of the abundance of these compounds. The workshop recommends a DOE enhancement of the program by examination of the relative role of Cloud Condensation Nuclei (CCN) derived from biogenic (dimethylsulfide, DMS) versus industrial (SO_2) emissions. The number density of CCN strongly influences shortwave forcing by clouds. It has been argued that CCN resulting from industrial emissions may have significantly perturbed shortwave forcing in industrial areas such as the eastern U.S., and may thereby be obscuring early detection of CO_2 induced warming. Wide areal coverage is needed because dimethylsulfide emissions are a strong function of ocean productivity and location. Chemical or isotope studies may distinguish industrial and biogenic sources.

4. It is recommended that the ARM program include the measurement of subvisual cirrus clouds. Studies of the radiative properties of such cirrus by aircraft measurements above and below such cirrus layers are necessary, perhaps in conjunction with lidars. Western tropical Pacific areas are important for such studies, particularly cirrus anvils of high cumulus which can act as climate forcers.

5. It is recommended that the ARM program include a measurement of surface insolation, especially in the presence of clouds; adding a measurement for photosynthetically active radiation, 0.4 to 0.7 μm, would be valuable in order to determine how cloud cover changes would affect agricultural productivity.

6. The workshop suggests that within the Long Term Observing Planning effort of NOAA, attention be given to developing an improved climatology of CCN and Ice Forming Nuclei (IFN). Large geophysical-scale and long-time monitoring of CCN and IFN is necessary to understand the present concentrations and the potential for future modifications.

These studies, especially measurements of water substance, should be considered as a test-bed for models. The western Pacific was suggested as an important site because of the large amount of convection, high water vapor concentrations, and sensitivity to El Nino perturbations. On the other hand, high latitude sites are highly sensitive to water vapor positive feedback, and thus might provide earlier indications of greenhouse warming. It was also suggested that there be a strong link to atmospheric chemistry programs. In addition to sulfate, it was observed that increments in tropospheric O_3 concentrations may be contributing to IR forcing, in an amount comparable to incremental changes in CO_2 and methane.

In addition to process studies, these measurements would provide data sets against which to compare GCM performance, enhancing the value of proposed GCM intercomparisons. Suggested intercomparisons include:

1. Snow feedback and its interaction with other feedbacks.

2. Distributions of water vapor, liquid water, and ice in the atmosphere.

3. Outgoing long- and shortwave fluxes derived from ERBE observations.

4. Latitudinal and longitudinal fluxes of water and energy in the atmosphere, and by implication, energy in oceans.

5. Radiative forcing in a 2 x CO_2 atmosphere, separately in clear and cloudy regions.

REPORT AND RECOMMENDATIONS OF THE PANEL ON OCEAN INTERACTIONS AND SEA-ICE RESPONSE

This working group considered the major feedback effects of the oceans on global climate which require an understanding to improve the predictive capability of climate models. It is assumed that advanced climate models will couple atmospheric and oceanic processes, and include realistic representations of biogeochemical processes which are crucial to climate feedbacks. Three processes were identified as being of high priority for research: the uptake and sequestering of CO_2 by the ocean; the transfer of heat across the air-sea interface and subsequent transport into the ocean interior; and the area, extent, and mass balance of sea-ice which dominates sensible heat fluxes at high latitudes. The uptake of CO_2 creates an indirect feedback on climate, modifying atmospheric forcing, due to anthropogenic emissions forcing, and potentially buffering atmospheric CO_2 levels on geological time-scales. Although heat transfer between the ocean and atmosphere is not a feedback process <u>per se</u>, it introduces a time constant into the relationship between atmospheric forcing and response. This delaying effect must be better understood to predict the timing and magnitude of the atmospheric response. The size of this time constant suggests that the ocean may serve as an effective calorimeter for global change. Ocean-atmosphere-sea-ice interactions are crucial to the evaluation of global climate response because current climate models represent a wide range of sensitivity.

The working groups made a number of specific recommendations for observational and modeling efforts to increase an understanding of key processes.

1. It is recommended that measurement of fluxes of CO_2 across the Air-sea Interface be supplemented.

The ocean influences climate by absorbing part of the CO_2 added to the atmosphere by human activities. The panel recommends research to better define the rate of CO_2 uptake and the mechanistic processes that regulate this rate, which must be understood if the evolution of the atmospheric CO_2 concentration is to be reliably predicted. This effort, as supported by DOE, has had, and should continue to have, two aspects.

The first aspect involves research to measure and model fluxes of CO_2 into and within the oceans. Current work should be continued, such as measuring the distribution of total CO_2, total alkalinity, and pCO_2 in oceanic surface waters, measuring the distribution of total CO_2 and total alkalinity within the ocean, and development of three-dimensional ocean GCMs. Research should be extended to include ^{14}C and other tracers which can improve our understanding of carbon transport, and can be used to validate and calibrate models. Studies of the time-varying distribution of O_2 in air should be undertaken because they will provide a definitive estimate of the net rate of CO_2 addition to the atmosphere and oceans. O_2 can be used in this way because it is linked with CO_2 by combustion, photosynthesis, and respiration, but is far less soluble in seawater, thereby eliminating uncertainties from gas exchange in mass balance calculations.

The second aspect involves experimental and modeling studies to achieve a mechanistic understanding of how ocean chemistry, biogeochemistry, and circulation fix the surface water pCO_2 field and thereby control air-sea fluxes. The southern ocean should have first priority. In addition to being an important site of anthropogenic CO_2 uptake, it is thought to have played a large role in regulating ice age pCO_2, and is considered to be a region where humans can conceivably influence CO_2 removal. One focus of mechanistic research should be in the area of ecosystems and should focus on understanding how ecosystem dynamics limit primary production and inorganic carbon removal, as particulates and as dissolved organic carbon (DOC), from eutrophic surface waters. Regeneration of carbon in particles and DOC, which releases CO_2 that can be mixed back up to the surface, should also be studied. This research should place a heavy emphasis on moored instruments that can return a high-resolution, long-term record of ocean chemistry, biology, and circulation. We also recommend implementation of a large-scale sampling program for the study of the surface water nutrient distributions to be carried out in conjunction with measurements of the carbon system parameters. This work would yield maps of the time-varying nutrient distributions in oceanic surface waters. Such maps would be useful for calibrating and testing models that account for the changing concentration of surface water CO_2, which is linked to nutrients by photosynthesis and respiration. Finally, the panel recommends *in situ* and satellite studies of ocean color. Measurements of ocean color provide the only possibility for long-term monitoring of variables related to biological productivity that give high spatial and temporal resolution.

The study of paleoclimate has also led to important insights into mechanisms that control climate and ocean chemistry. It is important to be alert to the implications of continued work in this area as a means of improving understanding of oceanic and climate processes.

2. The working group endorses the NOAA Atlantic Climate Change Program Plan which has the following goals:

a. To monitor, describe, and model the space time variability of the large-scale meridional circulation of the Atlantic Ocean and its role in producing variability of SST, sea ice, and salinity over the Atlantic Ocean on seasonal, annual, and interannual time-scales.

b. To determine the response of the global atmosphere to persistent SST and sea ice anomalies in the Atlantic Ocean, and to develop coupled ocean-atmosphere models to simulate and predict seasonal to decadal changes over and around the Atlantic Basin.

c. To design a program of observations to monitor the changes in the conveyor belt circulation, and to develop a suitable modeling program to assimilate these observations to help understand the mechanisms that determine the fluctuation of the conveyor belt circulation.

The NOAA program should be supplemented with transient tracer data to improve understanding of deep-ocean circulation.

The ocean offers special opportunities for the detection of global warming because of the favorable signal-to-noise ratio, compared to atmospheric measurements. Roemmich and Wunsch (1985)* have shown that substantial changes are taking place in the North Atlantic. A warming of 0.10° occurred between 1960 and 1980, between 1 km and 2 km over wide areas of the subtropical North Atlantic. It has been suggested that warming at the base of the thermocline can be monitored by remote acoustic methods. This strategy is being tested in ocean circulation models. Conventional, high-resolution hydrographic sections may be as effective for detection of these large-scale changes in ocean temperature.

It is recommended that model studies of greenhouse warming with coupled atmosphere-ocean models be undertaken to determine the best observational strategy. The study of transient tracer data will be useful, because the transient warming will penetrate the ocean in much the same way.

3. It is recommended that sea ice dynamics be included in atmospheric circulation models, especially those to be coupled to the ocean circulation. This will allow feedback effects due to ice transport and lead formation to be addressed, and will help to identify key inadequacies in the high latitude wind fields generated by atmospheric models. It will also clarify how to improve formulations of ice dynamics, thickness distribution, and transport in order to achieve more accurate representation of overall polar feedbacks in coupled models. The modeling experiments will require validation, using time-series data on sea ice thickness distribution and velocity obtained from measurements. Continued model development and verification using observed forcing fields will also be required.

The present uncertainties about ice-albedo and ice-cloud-radiation feedbacks must be reduced by analysis of *in situ* and satellite measurements. The purposes of this effort are: to acquire accurate estimates of surface radiation fluxes, cloud properties, and atmospheric soundings for at least one year on a station in the Arctic Ocean; to analyze these data together with periodic, aircraft-borne spatial surveys of solar radiation and surface temperature, and produce a data set for comparative and calibration analyses of satellite flux, sounder and

*Roemmich, D. and Wunch, C., 1985: Two transatlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. Deep Sea Res. 32: 619-664.

imager data; and to establish accurate retrieval procedures to determine the net solar and long-wave fluxes at the top of the atmosphere, the upward long-wave flux at the surface, and the net radiative effect of the intervening atmospheric layer. The established procedures should be applied to ERBE and other satellite data to estimate the net radiative feedback effect by comparison of ocean areas with and without sea ice cover. Subsequent studies should use the insights into polar radiative feedbacks, and the calibrated satellite-based radiation data, to improve and test parameterizations of polar radiative feedbacks in atmospheric general circulation models.

These aspects of high priority sea-ice response research should be linked to the developing programs of DOI/USGS (monitoring and research on the behavior of snow and ice, and their coupling with climate), NOAA (role of sea-ice in air-sea sampling), and NSF (Arctic Systems Science).

REPORT AND RECOMMENDATIONS OF THE PANEL ON TERRESTRIAL ECOSYSTEMS

Several aspects of biosphere-atmosphere interactions play a role in regulating the climate system. At rapid time-scales, evapotranspiration through terrestrial vegetation is a major factor in controlling atmospheric moisture content on regional-to-continental scales. The water vapor flux influences radiative properties of the atmosphere, surface energy balances, and cloud formation, which is a factor in global albedo. Terrestrial ecosystems play an important role in the global biogeochemical cycles. Seasonality in carbon exchanges between the atmosphere and terrestrial ecosystems cause an annual cycle in atmospheric CO_2 concentration. Terrestrial ecosystems regulate atmospheric CH_4 and N_2O concentrations, and strongly influence emissions of substances (e.g., nitric oxide and isoprene) that are precursors to tropospheric ozone. On longer time-scales, the structure of terrestrial ecosystems complexes (species composition, biomass, turnover rates) change, and these changes feedback on climate.

A broad research question stems from these interactions between the atmosphere and terrestrial ecosystems: How do terrestrial ecosystems modulate the response of the atmosphere to anthropogenic forcing from CO_2 emissions and land use? Specifically, how does the biosphere interact via short-term physiological and biological controls over water, energy, and albedo; and how does the terrestrial biosphere interact with global change via the carbon cycle?

Three areas of activity are timely when addressing this broad question: Whole-Ecosystem Controlled Experiments, Terrestrial-Atmosphere Flux Measurements, and Global Ecosystem Modeling.

1. Concepts, data, and models derived from laboratory studies must be extended to true field conditions, and this can be done with the current technology in Whole-Ecosystem Controlled Experiments. Particular attention needs to be given to those ecosystems with carbon storage and carbon fluxes great enough to have a significant impact on global carbon cycling, should they respond to CO_2 enrichment of the atmosphere or to climate change. In this regard, large stature ecosystems (i.e., forests with large biomass and slower dynamics, and mid- to high-latitude soil systems with large organic carbon pools) require specific attention.

Because of their relevance to carbon cycle and climate issues, realistic field experiments with elevated CO_2 concentrations are a high priority. Such experiments will clarify the role of terrestrial systems as a sink for CO_2. They will provide data for parameterization and evaluation of models describing the effects of increasing atmospheric CO_2 concentration on terrestrial carbon and the more general characteristics of terrestrial ecosystem carbon dynamics, such as the allocation of photosynthetically fixed carbon when plant community interactions are modulating plant growth. In addition to contributions toward the resolution of specific carbon cycle issues, Whole-Ecosystem Controlled Experiments are needed to test the consistency and robustness of a number of general ecological principles derived during the last decade. Plant physiological and microbial concepts are already being tapped to make ecosystem models of substantially more generality, a critical requirement of global change studies.

2. Terrestrial-Atmosphere Flux Studies should be included as a component of sites intended to evaluate the physical and chemical properties of the atmosphere. ARM can contribute to field ecological studies by adding measurements of surface fluxes -- sensible and latent heat, and CO_2 -- at long-term observation stations.

3. The field activities discussed above need to be set into a global perspective via a new emphasis on the development of Global Ecosystem Models. Global ecological models are needed for predicting changes in the earth system over decadal time-scales due to effects of the biota on surface energy balance, hydrology, and the carbon cycle. The interactive linkage between model development and field studies is as essential to the development and parameterizations of Global Ecosystem Models as is that between GCMs and field-centered data acquisition activities such as ARM. Global ecosystem models with the following attributes are needed:

a. The models must be global in extent and geographically subdivided to about 50 km resolution.

b. The models must incorporate physiological and biophysical interfaces between the atmosphere and terrestrial ecosystems.

c. The models must describe biogeochemistry because of its importance in the global carbon cycle that controls atmospheric CO_2 and CH_4 concentrations.

d. The models must describe population and community processes with time constants ranging from several years to centuries. Community changes may dominate physiological-biophysical and biogeochemical cycling, so that they are critical to understanding options for human uses of ecosystem resources.

The development of global ecosystem models parameterized with field data meshes with the long-term goal of developing a credible 50-year simulation of the Earth system of global climate and global biogeochemical models.

Although many observational, process, and model studies of ecological systems are presently being organized by several agencies, the integrative concepts in the three areas of activity recommended here are not being addressed.

APPENDIX

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