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Pacific Northwest Laboratory Annual Report for 1994 to the DOE Office of Energy Research

**Part 2: Atmospheric and Climate Research
April 1995**

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated by Battelle Memorial Institute
for the U.S. Department of Energy**

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**Pacific Northwest Laboratory
Annual Report for 1994 to the
DOE Office of Energy Research**

Part 2: Atmospheric and Climate Research

Staff Members
of Pacific Northwest Laboratory

April 1995

Prepared for
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Pacific Northwest Laboratory
Richland, Washington 99352

MASTER

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Preface

This 1994 Annual Report from Pacific Northwest Laboratory (PNL) to the U.S. Department of Energy (DOE) describes research in environment and health conducted during fiscal year (FY) 1994. This year, the report consists of two parts, each in a separate volume.

The two parts of the report are oriented to particular segments of the PNL program, describing research performed for the DOE Office of Health and Environmental Research (OHER) in the Office of Energy Research. Each part consists of project reports authored by scientists from several PNL research departments, reflecting the multidisciplinary nature of the research effort.

The parts of the 1994 Annual Report are as follows:

Part 1: Biomedical Sciences

J. F. Park, Program Manager
F. T. Cross, Report Coordinator
C. C. Lumetta, Editor

Part 2: Atmospheric Sciences

W. R. Barchet, Program Manager
G. P. O'Connor, Editor

Activities of the scientists whose work is described in this annual report are broader in scope than the articles indicate. PNL staff have responded to numerous requests from DOE during the year for planning, for service on various task groups, and for special assistance.

Credit for this annual report goes to the many scientists who performed the research and wrote the individual project reports, to the program managers who directed the research and coordinated the technical progress reports, to the editors who edited the individual project reports and assembled the two parts, and to Ray Baalman, editor in chief, who directed the total effort.

Previous Annual Reports in this series:

1951	HW-25021, HW-25709
1952	HW-27814, HW-28636
1953	HW-30437, HW-30464
1954	HW-30306, HW-33128, HW-35905, HW-35917
1955	HW-39558, HW-41315, HW-41500
1956	HW-47500
1957	HW-53500
1958	HW-59500
1959	HW-63824, HW-65500
1960	HW-69500, HW-70050
1961	HW-72500, HW-73337
1962	HW-76000, HW-77609
1963	HW-80500, HW-81746
1964	BNWL-122
1965	BNWL-280, BNWL-235, Vol. 1-4; BNWL-361
1966	BNWL-480, Vol. 1; BNWL-481, Vol. 2, Pt. 1-4
1967	BNWL-714, Vol. 1; BNWL-715, Vol. 2, Pt. 1-4
1968	BNWL-1050, Vol. 1, Pt. 1-2; BNWL-1051, Vol. 2, Pt. 1-3
1969	BNWL-1306, Vol. 1, Pt. 1-2; BNWL-1307, Vol. 2, Pt. 1-3
1970	BNWL-1550, Vol. 1, Pt. 1-2; BNWL-1551, Vol. 2, Pt. 1-2
1971	BNWL-1650, Vol. 1, Pt. 1-2; BNWL-1651, Vol. 2, Pt. 1-2
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1990	PNL-7600, Pt. 1-5
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1992	PNL-8500, Pt. 1-4
1993	PNL-9000, Pt. 1-4
1994	PNL-10500, Pt. 1-2

Foreword

The U.S. Department of Energy's (DOE) Office of Health and Environmental Research (OHER) atmospheric sciences and carbon dioxide research programs provide DOE with scientifically defensible information on the local, regional, and global distributions of energy-related pollutants and their effects on climate. This information is vital to the implementation of the National Energy Policy Act of 1992. This volume reports on the progress and status of all OHER atmospheric science and climate research projects at the Pacific Northwest Laboratory (PNL).

PNL has had a long history of technical leadership in the atmospheric sciences research programs within OHER. Within the Environmental Sciences Division (ESD) of OHER, the Atmospheric Chemistry Program (ACP) continues DOE's long-term commitment to understand the local, regional, and global effects of energy-related air pollutants. Research through direct measurement, numerical modeling, and analytical studies in the ACP emphasizes the long-range transport, chemical transformation, and removal of emitted pollutants, photochemically produced oxidant species, nitrogen-reservoir species, and aerosols. The Atmospheric Studies in Complex Terrain (ASCOT) program applies basic research on the structure and evolution of the atmospheric boundary layer over inhomogeneous terrain to DOE's site-specific and generic mission needs in site safety, air quality, and climate change.

Research at PNL provides basic scientific underpinnings to DOE's program of global climate research. Research projects within the core carbon dioxide and ocean research programs are now integrated with those in the Atmospheric Radiation Measurements (ARM), the Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP), and Quantitative Links programs to form DOE's contribution to the U.S. Global Change Research Program. Climate research in the ESD has the common goal of improving our understanding of the physical, chemical, biological, and social processes that influence the Earth system so that national and international policymaking relating to natural and human-induced changes in the Earth system can be given a firm scientific basis.

The description of ongoing atmospheric and climate research at PNL is organized in two broad research areas:

- **Atmospheric Research**
- **Climate Research**

This report describes the progress in FY 1994 in each of these areas. A divider page summarizes the goals of each area and lists the projects that support research activities.

Atmospheric
Research

Atmospheric Research

Atmospheric research at Pacific Northwest Laboratory (PNL) occurs in conjunction with the Atmospheric Chemistry Program (ACP) and with the Atmospheric Studies in Complex Terrain (ASCOT) Program that are managed by the U.S. Department of Energy (DOE) Office of Health and Environmental Research (OHER) Environmental Sciences Division (DOE/ESD). A major change in how these programs are managed occurred in FY 1994. Solicitations for proposals and peer review were used to select research projects for funding in FY 1995. Nearly all ongoing projects were brought to a close in FY 1994. Therefore, the articles in this volume include a summary of the long-term accomplishments as well as the FY 1994 progress made on these projects.

PNL has had a long history of program leadership in DOE atmospheric chemistry research. PNL staff regularly interact with DOE/ESD on emerging scientific issues pertaining to air quality, global chemistry, and ozone. ACP research at PNL focuses on the fate of energy-related pollutants as they are transported and processed in the atmosphere. In FY 1994, chemical modeling studies and analyses of field study data from FY 1992 and FY 1993 focused on the contribution of various ozone production and destruction processes to the formation of the observed vertical profiles of ozone concentrations in the lower marine troposphere. By virtue of a successful research proposal funded through FY 1997, PNL will continue to be a leader in ACP research on ozone formation and distribution.

After many years of operation almost exclusively as a research tool for PNL projects within the ACP, PNL's Gulfstream 1 (G-1) aircraft was formally recognized as a DOE research facility. As such, in FY 1995, DOE will support up to 250 hours of G-1 research flight hours to scientists funded by the ACP at PNL, other national laboratories, and universities, and make some of those hours available to scientists working on non-ACP studies whose goals are consistent with those of the ACP.

All of PNL's ASCOT projects contributed in FY 1994 to the ASCOT focus on understanding the complex boundary-layer flow patterns that affect DOE's Rocky Flats Plant near Denver, Colorado. However, many projects also addressed the processes by which complex terrain and energy exchanges over heterogeneous surfaces govern the interaction of local air flows with large-scale synoptic circulations in other areas such as the DOE Hanford Site near Richland, Washington; the Oak Ridge, Tennessee area; and the Grand Canyon and Colorado Plateaus and Basins area in Arizona and Utah. While all but the ASCOT Science Director project closed in FY 1994, PNL was assured of being a leading force in ASCOT by being awarded six research proposals for FY 1995 to FY 1997.

The following articles present summaries of the progress in FY 1994 under these research tasks:

- Continental and Oceanic Fate of Pollutants
- Research Aircraft Operations
- ASCOT Program Management
- Coupling/Decoupling of Synoptic and Valley Circulations
- Interactions Between Surface Exchange Processes and Atmospheric Circulations
- Direct Simulations of Atmospheric Turbulence.

Continental and Oceanic Fate of Pollutants

Principal Investigators: C. M. Berkowitz, M. K. Brown (Applied Physics Center, PNL), K. M. Busness, E. G. Chapman, R. C. Easter, R. D. Saylor, W. J. Shaw, S. B. Smyth^(a), J. M. Thorp

The Atmospheric Chemistry Program (ACP) is one of DOE's multi-laboratory programs of research on atmospheric processes. The objective of the ACP is to provide information to DOE on the sources of, the transformations undergone by, and the ultimate fate of airborne chemicals associated with energy production.

FY 1994 Accomplishments

A major emphasis of research activities during FY 1994 was an analysis of data collected during the FY 1992 and FY 1993 field studies over the western North Atlantic Ocean. PNL scientists carried out two major field programs over 2 years to evaluate the potential for long-range transport of ozone that originated from North American emissions of oxides of nitrogen and volatile organic compounds (VOC). This investigation consisted of modeling work and analysis of the data collected during the field program. Other major projects carried out under ACP at PNL during FY 1994 included development of techniques to assess the spatial and temporal distribution of trace gases, a new method to perform sensitivity studies for large chemical transport models, completion of analysis of data collected during the 1991 field study of the oil well fires in Kuwait, a modeling study of aerosol optical thickness over the western North Atlantic, an evaluation of the potential for trans-Atlantic transport of sulfur, and preparation of proposals for research to be done during FY 1995-1997.

(a) School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia.

Analysis of Observations from the 1992 and 1993 Field Campaigns

Data collected over the western North Atlantic between August 21, 1992, and September 14, 1992, were used to show that maximum ozone mixing ratios typically occurred above or at the top of the marine boundary layer (MBL) rather than at the surface. This feature was most pronounced when the thermal structure of the atmosphere was well mixed up to approximately 1.5 km, with a stable layer above this height. Under these conditions, the ozone mixing ratio above the top of the MBL was typically twice that within the boundary layer, with typical values of 50-70 parts per billion (ppb), and in some cases much higher, aloft and ~20-30 ppb near the surface, with an abrupt transition (~0.5 km) separating the two domains. Data and modeling studies from the 1992 DOE/ACP sampling campaign were used to support the hypothesis that convective activity associated with synoptic scale fronts several days before the arrival of the air masses into the sampling domain produced a well-mixed layer of ozone through a deep column of the atmosphere. The association with frontal activity, in conjunction with observations by other investigators, suggests that much of this ozone was of recent

stratospheric origin (Berkowitz et al. 1994a). High pressure developing behind these frontal systems and boundary layer turbulence then produced a subsidence inversion that decoupled air near the surface from air aloft.

As these columns of air moved eastward, surface removal over land reduced the ozone mixing ratio within the boundary layer, but had little effect aloft (Figure 1). Upon reaching the cooler waters off the maritime provinces, the mixing process and surface deposition of ozone effectively stopped. At this time, the ozone profiles were observed to have much higher mixing ratios in the free troposphere than near the surface, with an abrupt transition region indicating the maximum height of the convective boundary layer from which the surface deposition occurred.

Measurements taken during the 1992 and 1993 field studies were also used to identify evidence of long range transport of ozone that was photochemically generated within urban areas of North America. A number of events were identified through statistical correlations between ozone, carbon monoxide, and other pollutants. Each of these events was detected within the marine boundary layer in advance of eastward-moving cyclonic systems associated with cold fronts. The potential for further transport during these events was evaluated with isentropic forward trajectories from the sampling domain, indicating that subsequent long-range transport occurred for the 1992 events, but not for the 1993 events (Figure 2). By using the daily flux associated with these specific events in conjunction with earlier estimates of the mean daily flux, we have estimated that 17% of the flux of excess ozone into this region is associated with eastward-moving cyclones that occur 6% of the time; 80% of the ozone is associated with other synoptic patterns, and little or no transfer occurs 35% of

the time. Extrapolating these numbers to the coastline of North America allows us to evaluate the mass transfer of photochemically generated ozone to the western North Atlantic during summer; the total number, 90 Gmol, is 30% smaller than previous estimates made using surface observations and modeling techniques (Berkowitz and Saylor 1994).

An extensive review of organic acid data collected during the 1992 field study was also completed during FY 1994. Formic and acetic acids are ubiquitous vapor- and aqueous-phase atmospheric constituents that are primary contributors to precipitation acidity in remote regions of the world. Many uncertainties exist about the gas phase distribution and spatial variability of these acids, because previous measurement techniques necessarily required spatial and temporal integration, severely limiting data resolution. Using a Sciex Model 6000E tandem mass spectrometer that was specifically modified for aircraft sampling, we gathered information on the distribution aloft of these acids over the western North Atlantic. The sensitive, specific, and real-time measurements provided by the mass spectrometer allowed the first true spatial profiles of these species in the atmosphere.

The analysis indicated that substantial temporal, vertical, and horizontal variability can exist for gaseous organic acids in this region of the North Atlantic. Examples of this variability are shown in Figure 3, where formic acid, acetic acid, and ozone mixing ratios are shown for a vertical profile, boundary layer transect, and free tropospheric transect conducted on August 31, 1992. Mixing ratios of both acids vary by more than a factor of 5 throughout the depth of a 2400-m profile, while ozone mixing ratios varied by a factor of 2. Highest organic acid mixing ratios observed during the field study were associated with air

FIGURE 1. A Time-Height Cross Section for a Modeling Study to Investigate the Layering of Ozone Observed During the 1992-1993 Field Studies. The STEM code of Saylor et al. (1994) was used to quantify the rate of ozone production vs. loss through surface depletion, with the resulting layer shown above.

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FIGURE 2. An Isentropic Forward Trajectory for August 26, 1992, Showing Eastward Transport of Air After a "Pollution Event" Detected off the Coast of Nova Scotia. The "ball and stick" figure shows the location of the parcel every 24 hours after its release, with the ball placed at the height of this surface.

FIGURE 3. Formic Acid (thin line), Acetic Acid (thick line), and Ozone (xx) Mixing Ratios Observed on August 31, 1992, for a) Profile 2 (ascent spiral) at 43.9°N, 60.0°W; b) Transect 1 Conducted in the Boundary Layer at an Altitude of 333 m Between 44.50°N, 62.35°W and 43.97°N, 60.33°W; and c) Transect 2 Conducted in the Free Troposphere at an Altitude of 1853 m Between 44.04°N, 60.16°W and 44.68°N, 62.62°W. The data gap appearing between 61.5°W and 61.3°W for Transect 2 results from a zero check conducted on the mass spectrometer as part of the inflight quality assurance program.

of continental origin, while lower mixing ratios were seen in air of polar and marine origin. These associations are consistent with previous ground-based studies. Mixing ratios of the two acids were strongly correlated ($r^2 > 0.70$) throughout the study region. Details of this work are presented elsewhere (Chapman et al. 1995; Spicer et al. 1994).

Modeling Studies

Analyzed meteorological fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used to drive a modified version of the PNL global chemistry model (Luecken et al. 1991) applied to the atmospheric sulfur cycle (Berkowitz et al. 1994b). It has been postulated that scattering of sunlight

by aerosols can significantly reduce the amount of solar energy absorbed by the climate system. Aerosol measurement programs alone cannot provide all the information needed to evaluate the radiative forcing as a result of anthropogenic aerosols. Comprehensive global-scale aerosol models, properly validated against surface-based and satellite measurements, are a fundamental tool for evaluating the impacts of aerosols on the planetary radiation balance. Confidence bounds for models describing the spatial, temporal and physicochemical variation of aerosols must be evaluated before the models can be used for either scientific or policy-related purposes. Such an evaluation was the goal of this project within ACP.

Although our results must be regarded as preliminary, they demonstrate a general correspondence between simulations and observations in regions contaminated by anthropogenic sulfur aerosols (Figure 4). The simulated optical depth exhibits a similar pattern to the observations, with the largest values offshore from the coast of North America. The spatial structure of the bias can be assessed by examining the ratio of the simulated optical depth to that observed. The bottom panel of Figure 4 shows the log 10 of the ratio. A log scale is used because it provides a uniform resolution of positive and negative fractional errors. In another study (Benkovitz et al. 1994), we found that the lowest vertical level of the model accurately represents the spatial variability, temporal episodicity, and absolute magnitudes of surface concentrations measured by monitoring stations in Europe, Canada, New York State, and Barbados; more than 50% of the model concentrations were found to be within a factor of 3 of the observations.

In another modeling study completed this year, an evaluation was made of the conversion rates of SO_2 and NO_x ($\text{NO} + \text{NO}_2$) to sulfate

and nitrate within the Kuwait oil fire plumes of August 1991 (Smyth et al. 1994). The conversion rates were of scientific interest because these constituents can be implicated as precursors to acid rain, which was of concern during wet removal outside the region, and as deposits on soil and vegetation. The PNL Gulfstream-1 aircraft was used to sample the Kuwait oil fire smoke plume by flying horizontal transects across the plume normal to the mean wind direction. Concentrations of SO_2 , NO_x , and CO_2 were measured continuously, and time-integrated filter samples were also collected. We then used these measurements in conjunction with a Lagrangian mass conservation equation to evaluate these oxidation rates. Detailed analysis suggests that the oxidation rates of SO_2 and NO_x are best explained as second-order process with conversion rates of 1% and 2% h⁻¹, respectively, within 100 km of the source.

Chemical transport models can also be used to infer the temporal and spatial distribution of trace gas emissions using an increasingly vast network of atmospheric concentration data. These studies seek a spatial and temporal distribution of the trace gas emissions that will produce a modeled atmospheric concentration and isotopic composition consistent with that is observed. Current observational policy is focused on the accumulation of high-resolution atmospheric concentration and isotopic ratio data intended to constrain the location, magnitude, and isotopic composition of the surface sources of the trace gas. However, the smoothing of emissions by atmospheric transport processes will limit the information contained in these data to relatively low spatial and temporal resolutions and will result in unreasonably large error bounds on the inferred emissions distribution.

FIGURE 4. Observed (top) and Simulated (middle) Optical Depth and the Log 10 of the Ratio of Simulated/Observed (bottom) for October 23, 1986.

Work completed under ACP investigates the ability of the singular value decomposition (SVD) and the truncated singular value decomposition (TSVD) to produce a methane emissions estimate at the resolution of the chemical transport model with reasonable error bounds and investigate the ability of observations of the isotopic ratio of atmospheric methane to provide further constraints on the methane emissions distribution (Brown 1994, 1995). The results demonstrate that the SVD and TSVD analysis and solution techniques are useful tools for the inversion of atmospheric methane data. A latitudinal distribution of the methane emissions with reasonable error bounds is inferred at the resolution of the model.

The feasibility of applying adjoint sensitivity methods to the chemical kinetics of an atmospheric model was also investigated during FY 1994. An important aspect of chemical transport modeling of the atmosphere is the analysis of the sensitivity of the modeled responses to input parameters. For example, accurate simulations of chemical processes in the atmosphere require the imposition of reaction rate coefficients. These coefficients, obtained experimentally, always have an associated uncertainty, and it is expected that these uncertainties will propagate into the modeled response. A sensitivity study provides an estimate of the uncertainty in the response of the model given the uncertainty in the model parameters. Sensitivity analysis is also applicable to the model development process, where it can be used to test the sensitivity of the response to the model assumptions and in the formulation of inverse problems seeking the model parameters required to produce a modeled response consistent with observational data. The difficulty that arises in sensitivity studies is that the computational time required for the calculation of the model sensitivities can

be extreme. The adjoint method should greatly reduce these computational demands, allowing for more complete sensitivity studies in the future.

Future Work

A 3-year integrated field sampling and modeling program has been proposed for the eastern Pacific Ocean. This work will be done in close cooperation with scientists from Battelle Columbus and the University of California/Riverside. Primary objectives of the program are to 1) evaluate the relative significance of chlorine and hydroxyl radicals in the production of tropospheric ozone in a marine environment, and 2) characterize the chemical composition of air in a remote area of the Pacific. Data obtained under the program will help determine whether currently ignored chlorine-initiated reactions must be included in regional-scale analyses and ozone budgets, as recent laboratory and theoretical studies have indicated. The data will also serve as a benchmark for future air quality comparisons as increasing pollutant emissions from Asia influence the composition of air masses transported to the United States. First-year activities will center on instrumental preparation, logistical arrangements, and establishment of detailed sampling scenarios. A 4-week ground and airborne data collection program will be conducted during the second year. Efforts during the final year will focus on data analysis and preparation of open literature journal articles.

A separate program will focus on evaluation of a detailed global aerosol model, to be performed using satellite and surface-based aerosol optical depth data, and surface concentration and deposition data. The global aerosol model, which is being developed under separate funding, is coupled to a general circulation model (GCM) that assimilates observed winds

and temperature and predicts cloud water and precipitation. The aerosol model treats both anthropogenic and natural aerosols, including soluble inorganic species (sulfate, nitrate, ammonium), organic species, elemental carbon, and dust. It simulates the aerosol size distribution using the method of moments. Several 6-week simulations will be performed, and the simulations will be evaluated against available observations using an evaluation protocol developed during the project. Direct radiative forcing by anthropogenic aerosols and associated uncertainties will then be quantified using the aerosol model simulations and results of the model evaluation. Tropospheric aerosols have been identified as the largest uncertainty in anthropogenic forcing of climate. The goal of this research project is to reduce that uncertainty.

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Research Aircraft Operations

Principal Investigator: K. M. Busness

Other Investigators: O. B. Abbey, W. A. Garrity, R. V. Hannigan, and M. J. Warren

To fulfill a number of important national and DOE goals related to understanding the transport and transformation of energy-related pollutants and their impact on global climate issues, PNL operates a Gulfstream I (G-1) aircraft to obtain diagnostic environmental measurements aloft. The G-1 serves as an advanced airborne sampling platform, with the capacity to accommodate a wide variety of instrumentation in support of field measurement programs dedicated to achieving DOE's information needs. This aircraft resource, with associated measurement instrumentation and supporting personnel, is operated as a DOE/OHER/ESD Research Aircraft Facility that is made available to researchers from the national laboratories.

FY 1994 Accomplishments

Primary activities this year were maintaining the aircraft and continuing to upgrade the aircraft and instrumentation capabilities. No field programs were planned this fiscal year as researchers focused on analyzing and reporting data acquired in the ACP measurement campaigns conducted in the western North Atlantic in 1992 and 1993.

Planned improvements to the aircraft's data acquisition system have been completed with an upgrade to a 66-MHz 486 series processor, replacement of the 1/4-in. tape drive with a high-capacity Exabyte cartridge tape system, installation of a dual-format flexible disk drive for both 3 1/2-in. and 5 1/4-in. media, and installation of a larger hard disk drive. These enhancements greatly improve our capability to reliably acquire and display the high volume of high-speed data associated with the TAGA mass spectrometer, fine particle instruments, gust probe sensors, and aircraft attitude sensors. The upgraded system is observed to be significantly faster and is expected to eliminate marginal operational characteristics previously experienced when dealing with high-frequency parameters.

A Trimble Advanced Navigation Sensor Vector receiver, a state-of-the-art satellite

navigation system (GPS) was acquired for installation into the G-1. This low-power, light-weight system provides aircraft attitude information (azimuth, pitch, and roll angles) and altitude as well as standard latitude and longitude coordinates. This equipment is expected to provide the attitude data essential to gust probe and radiation sensor measurements. Initial ground-based tests indicate that angle movements of only a few tenths of degrees can be detected. Additional testing on the aircraft will determine if the resolution and response time of the system is adequate to replace the aging Litton Inertial Navigation System currently installed on the G-1.

A major reconfiguration of the research power system was undertaken to provide 230-volt power required by certain instruments and also to improve the cabin environment. Two inverter clusters (DC to AC converter systems) are being relocated in the aft fuselage, outside the interior cabin area. This configuration will reduce heat and free additional space within the cabin. Because most ACP research flights are conducted in the lower troposphere in an unpressurized cabin, excessive heat generated by instruments is often a problem in the aircraft cabin (for both instruments and researchers).

Improvements to post-collection data reduction and analysis capabilities were also accomplished with upgrades of the Sun workstation, including a faster processor, addition of an Exabyte cartridge tape drive to provide compatibility with the expanded data acquisition system recording capability, and addition of a 3-GB disk drive to provide fast access storage for the many large data files collected during a field project. Software upgrades of the basic operating system and Splus codes also were installed. This computer system runs specialized data processing software tailored to the aircraft data format and is often deployed to field operation sites to provide immediate evaluation of data and instrument systems performance for quality purposes and for use in subsequent mission planning. All these enhancements should greatly benefit aircraft operations during the increased activity expected in the next few years, as reflected in newly funded DOE programs.

Recognizing that the current aircraft instrument ensemble is inadequate in terms of sensitivity for some missions proposed in upcoming field programs, particularly those in the eastern Pacific region, several ACP participants have met to discuss and make recommendations regarding expected measurement problems, possible techniques to address those problems, and resources required. As a result, development tasks for necessary instruments have been undertaken and a policy agreement accorded, that such instruments will become part of the ACP "community property" resource ensemble. This is expected to greatly enrich instrument package options available to all ACP researchers.

The G-1 was subjected to a structural inspection in late FY 1994 as a result of an unexpected maintenance bulletin issued by Gulfstream Aerospace requiring x-ray and ultrasound examinations of wing and tail structures on all G-1 type aircraft. Minor-to-moderate metal corrosion was detected, making

it necessary to accomplish some major maintenance procedures to disassemble, repair, and reassemble principal wing components. The lengthy, labor-intensive process will be completed in calendar year 1994, making the aircraft ready for proposed FY 1995 field programs.

Future Work

Proposals selected by DOE for funding over the next 3 years suggest operations along the coastal eastern Pacific (Argonne National Laboratory, Brookhaven National Laboratory, Pacific Northwest Laboratory) and southeastern U.S. regions (Brookhaven National Laboratory), requiring 400-500 flight hours. After contracts are awarded, flight hours will be scheduled for FY 1995-FY 1997.

Meetings will be held in late FY 1994 or early FY 1995 to establish priorities for aircraft resources, identify potential collaborative interests, and develop flight schedules. To promote the most effective use of the aircraft, a Research Aircraft Facility Advisory Panel (RAFAP) is envisioned. This panel, with representatives from each participating national laboratory, the aircraft facility, and DOE program management, would evaluate requests for flight hours and associated aircraft support, on the basis of scientific objectives, feasibility of project design and needs, and cost, and make recommendations to the Director of DOE/OHER/ESD regarding award of resources. To assist the RAFAP in evaluating proposed aircraft activities, a Facility Request Form has been developed for requestors to provide details of flight plans, instrument needs, and other logistical concerns necessary to their programs.

In addition to ACP activities, the aircraft is expected to participate in ultraviolet-B ozone studies associated with tests conducted at the DOE Atmospheric Radiation Measurement Program's southern Great Plains site.

ASCOT Program Scientific Director

Principal Investigator: J. C. Doran

The objective of the ASCOT Program Scientific Director (APSD) project is to provide scientific leadership and coordination for the activities of the Department of Energy's (DOE) Atmospheric Studies in Complex Terrain (ASCOT) program.

FY 1994 Accomplishments

Principal FY 1994 activities included the following:

- a workshop for modelers in November 1993
- oversight of the peer review process of future ASCOT research
- presentation of invited paper at a meeting of the American Meteorological Society
- a meeting of the ASCOT Science Team in February 1994
- a planning meeting in May 1994
- support for meteorological measurements in the Front Range region of Colorado.

ASCOT Modelers' Workshop

A modelers' workshop was held in November 1994 in Santa Fe, New Mexico, with the assistance of staff from the Los Alamos National Laboratory. The theme of the meeting was comparing the performance of diagnostic and prognostic models for emergency response applications. Data from the 1991 tracer experiment in Colorado's Front Range formed the principal basis for evaluations of model performance. The meeting featured extensive discussions of each individual investigator's results, with particular attention given to assessing the limitations of various modeling approaches. As anticipated, diagnostic models

were shown to work well provided that dense wind field observation networks were available and extended forecasts were not required. The execution speeds of prognostic models on scales relevant to dispersion from the Rocky Flats Plant were considerably slower than those of diagnostic models, but show considerable promise for future applications.

Peer Review of Proposals for ASCOT Funding

For the first time, proposed ASCOT research was subject to a peer review process to determine which projects DOE would fund. A panel of 13 reviewers drawn from universities, industry, and non-DOE federal agencies was recruited and convened in December 1993 to evaluate 35 proposals from DOE and National Oceanic and Atmospheric Administration (NOAA) scientists. Results of this review were used as the basis for approving 18 proposals for funding during FY 1995-FY 1997.

Presentation of Invited Paper

In January 1994, an invited paper, "The Role of The ASCOT Program in Dispersion Studies in Complex Terrain," was presented at a joint meeting of the American Meteorological Society (AMS) and the Air and Waste Management Association in Nashville, Tennessee.

ASCOT Science Team Meeting

A meeting was organized for all ASCOT scientists in February 1994 in Salt Lake City, Utah. Participants presented results of their work in the previous year, including

simulations of tracer dispersion near the Rocky Flats Plant in Colorado using four-dimensional data assimilation of Front Range meteorology, parameterization of gravity wave drag in a mesoscale model, simulations of thermally induced flows in idealized valleys, and a novel method of representing windfields in terms of pseudo-dipole fields.

Planning Meeting

A planning meeting was held in Germantown, Maryland, in May 1994 for members of the Science Planning Group. The purpose of the meeting was to identify significant national problems to which members of the ASCOT community could contribute, to examine how the program might evolve or be restructured to address those problems, and conduct initial planning for the deployment of radar profilers and sodars for a field experiment planned for the summer and fall 1995.

Support for Meteorological Measurements

The NOAA Environmental Technology Laboratory (ETL) has maintained close ties

with the ASCOT program over the last decade and more. Funds were again provided to ETL to continue their measurement program in the vicinity of Eldorado Canyon. These data will be archived in the ASCOT data base maintained by Argonne National Laboratory, and some information will be used in the dissertation research of Mr. Clark King of ETL.

Future Work

The ASCOT program was subjected to a severe budget cut early in FY 1995 that places the future of the program in jeopardy. Because of this cut, APSD activities in FY 1995 will be limited. At least one planning meeting will be held with representatives of other DOE laboratories to explore possible new activities and areas of research to which program members can contribute. Discussions will also be carried concerning a possible new complex terrain boundary-layer initiative that may be prepared. To the extent possible, the APSD will also continue to coordinate the reduced scope of activities of ASCOT participants and will take steps to ensure the orderly termination of the program if that becomes necessary.

Direct Simulation of Atmospheric Turbulence

Principal Investigator: J. C. Doran

The objective of the Direct Simulation of Atmospheric Turbulence (DSAT) project has been to use advanced numerical models to simulate complex nonlinear dynamics in atmospheric flows. In addition, in cooperation with other PNL programs, the DSAT project jointly supported activities of the DOE's ASCOT program in experimental and analytical studies of atmospheric dynamics and their effects on diffusion of atmospheric pollutants.

FY 1994 Accomplishments

In FY 1994, principal accomplishments of DSAT included the following:

- continued support of Mr. James C. Barnard's graduate research program in numerical simulations of stable turbulent boundary layer flows
- support (with one other ASCOT project) of a post-doctoral appointment for Dr. Shiyuan Zhong to work in the boundary layer research group at PNL
- initiation of a study of the characteristics of drainage flows in Eldorado Canyon in Colorado's Front Range.

Simulation of Turbulence in Stably Stratified Flows

The DSAT program has been supporting Mr. Barnard's graduate research at the University of Washington under the direction of Professor Jim Riley. A linear stability analysis of the stratified boundary layer has suggested the hypothesis that, under conditions of strong and complete stratification, the boundary layer may thicken, and vertical transport may be enhanced. This concept is contrary to the tenets of traditional stable boundary layer theory. Because this hypothesis is based on the dynamics of the boundary layer just before to the onset of turbulence, it is necessary to determine if these ideas will hold in the fully

turbulent state. To this end, a direct numerical simulation (DNS) of the turbulent, stratified boundary layer is being carried out. With a DNS it is possible to study the transition of the initial instability to turbulence as well as the fully turbulent state at low Reynolds number; consequently, the DNS will permit testing the above hypothesis. This work will be the basis for a Ph.D. dissertation and for an article in a refereed journal, both to be submitted in 1995.

Post-Doctoral Support

Dr. Zhong continued for a second year on an Associated Western Universities (AWU) post-doctoral appointment during FY 1994. DSAT shared the cost of her second full year at PNL with another ASCOT research project. In DSAT, she carried out a series of numerical simulations with Colorado State University's Regional Atmospheric Modeling System (RAMS) on the effects of surface flux inhomogeneities on atmospheric circulations. These simulations were used to analyze the behavior of the planetary boundary layer over regions with sharply contrasting values of sensible heat fluxes. The work is relevant not only to ASCOT interests but to those of DOE's Atmospheric Radiation Measurement program as well. A journal article has been submitted to the *Journal of Climate* describing some of the work, and a second article, to be submitted to the *Journal of Applied Meteorology* is being prepared.

Eldorado Canyon Studies

In late summer and fall 1993, a 3-month measurement campaign was carried out in Colorado's Front Range near DOE's Rocky Flats Plant (RFP). Using sodars and radar wind profilers, ASCOT scientists sought to determine the characteristics of drainage flows in Eldorado Canyon, which lies to the northwest of the RFP, and to investigate the circumstances under which these flows might affect the local wind conditions at the RFP. DSAT helped support the measurement program, and the subsequent analysis of the data collected during that period.

Sodar records suggest that thermally enhanced down-valley flows in Eldorado Canyon can be usefully classified as either shallow, with peak winds occurring in the lowest 150-200 m near the canyon mouth, or deep, with moderate-to-strong winds extending over depths of 400 m or more. Under shallow wind regimes, little evidence exists that the local winds at the RFP are affected by Eldorado Canyon winds; during deep wind periods, the winds at RFP may blow from the northwest but the role of the canyon is problematic. Numerical simulations suggest that air in the canyon may spill over the canyon ridges, flowing down over the mountain-plains interface near the RFP. Air flowing out of the canyon mouth, however, seems less likely to affect the RFP. However, simulations by others have shown the possibility of divergent flow from the canyon mouth moving toward the RFP.

Equally significant is the finding that deep flows in Eldorado Canyon are strongly correlated with deep (approximately 3000 m or more) mixed layers near sunset, as determined from the Stapleton rawinsonde soundings. Conversely, when the mixed layer is shallow, the Eldorado Canyon flows are much more likely to be shallow. The mechanism responsible for this dependence is currently being investigated with the aid of a numerical mesoscale model, and the results will be submitted for publication. In the meantime, this observed

correlation may provide a tool for forecasting the winds near the RFP and the occasions when Eldorado Canyon winds are likely to influence them.

Future Research

FY 1994 marked the end of the DSAT project, and this report provides an opportunity to briefly summarize some previous contributions of the project. In the educational area, the program has provided support for Mr. Barnard to pursue a Ph.D. in computational fluid dynamics at the University of Washington and partial support for K. Jerry Allwine's research for his Ph.D. from Washington State University. DSAT also jointly supported a post-doctoral position for Dr. Zhong for 2 years. Dr. Zhong was subsequently hired as a research scientist in the Boundary Layer Meteorology group at PNL.

DSAT has supported studies—observational, analytical, and numerical modeling—covering a variety of regions ranging from Tennessee and Colorado to Washington. The project has provided funds for tracer studies, mass balance studies, and measurements of wind and temperature profiles during ASCOT field campaigns. Its area of concentration, however, has been in the use of numerical models to investigate the interactions of ambient winds and local circulations generated by thermal and topographical forcing mechanisms. In this area it has examined the development of the deep nocturnal boundary layer found above the Roan Plateau in Colorado, and the role of shear (between the low-level thermally driven flows and the large-scale overlying wind field) that enhances turbulent mixing of the cold surface layer air upward to form a deep mesoscale boundary layer. DSAT has analyzed the influence of synoptic winds above the ridgetops of the Tennessee Valley on the wind fields near the valley floor. Found to be a major factor in this region was pressure-driven channeling, in which the winds below the ridgeline are driven by the

along-valley pressure gradient component in the valley that can result in valley winds that blow in opposition to the along-valley wind direction components above the valley. As part of a joint study with another ASCOT project, DSAT not only demonstrated the complexity of the factors influencing valley wind fields but also provided an approach toward developing practical forecasting guidelines for these difficult-to-predict winds. DSAT obtained new insights into the mechanisms responsible for the regional drainage winds that occur regularly over the Hanford Site in Washington during spring and summer months. Such winds become significant when a thermal low east of the Cascade Range draws the cooler air west of the Cascade Range across the mountains. The study again demonstrated the ability of advanced numerical models to contribute to both basic and applied meteorological research needs. DSAT's most recent focus on the wind fields over the RFP in Colorado and their dependence on local thermal and terrain features continued this approach.

A principal finding of the DSAT project was that it is often unwise to make definitive statements about the expected behavior of wind and temperature features and dispersion meteorology in an area of complex terrain without careful analysis and study.

An early goal of the ASCOT program was to achieve "transferability," i.e., the ability to transfer readily what was learned in one

location to another location. The reality of the situation has turned out to be more complicated. Although much has been learned about flows in complex terrain, and many useful guidelines have been developed, it is now clear that reliance on guidelines without supplemental studies can often be badly misleading. In this sense, "transferability" has proven to be elusive. Nonetheless, development of a suite of tools—including sophisticated numerical modeling techniques—has at least provided the means to carry out such supplemental investigations far more efficiently and completely than was previously possible. During its lifetime, DSAT has played a significant role in demonstrating this approach in its treatment of a variety of interesting and important problems.

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Interactions Between Surface Exchange Processes and Atmospheric Circulations (IBSEPAC)

Principal Investigator: W. J. Shaw

Other Investigators: R. R. Kirkham, J. M. Hubbe, S. Zhong, and M. S. Wigmosta

The purpose of the Interactions Between Surface Exchange Processes and Atmospheric Circulations (IBSEPAC) program was to improve our understanding of the interactions between surface fluxes of heat, momentum, and moisture, and the structure of the atmospheric boundary layer. The general objectives of the program were to 1) establish techniques for measuring and describing appropriate, representative values of these fluxes for use in parametric representations of their effects; 2) measure properties of the atmospheric boundary layer that are sensitive to the surface fluxes; 3) examine possible feedbacks that boundary layer properties may have on the surface characteristics; 4) evaluate systematically, through the use of advanced numerical models, the effects of variable surface fluxes of heat, momentum, and moisture over heterogeneous surfaces on the local and regional circulations in the planetary boundary layer; and 5) study the diurnal and seasonal variability in these processes. Specific objectives for 1994 included 1) completing the analysis of the 1992 field data and publishing at least one article describing the results; 2) evaluating surface modules used to represent surface-atmosphere exchange in heterogeneous terrain in the context of the IBSEPAC data and publishing the results; 3) concluding the evaluation of the wind profiling radar, including an assessment of its capabilities as a momentum flux profiling system and publishing the results; and 4) installing and evaluating the laser scintillometer system so that it will be generally useful to a variety of DOE ASCOT projects.

FY 1994 Accomplishments

Surface-Atmosphere Exchange through a Semi-Arid Mixed Canopy

Energy balance and turbulence flux data were collected in 1992 in a mature shrub-steppe environment located 2 km east of the Hanford Meteorological Station (HMS) on the Hanford Site. This plant community is very patchy with distinct areas ($< 10 \text{ m}^2$) of either bare soil or cheatgrass mixed with mature sagebrush. Measurements of fluxes of heat, moisture, and momentum were made at a single point in the surface layer, while measurements of canopy energetics and soil heat and moisture budgets were made over each of the three surface elements (sagebrush, cheatgrass, and bare sandy soil). We evaluated two one-dimensional models: GAPS (General-Purpose Atmosphere-

Plant-Soil Simulator, developed at Cornell University) and SHAW (Simultaneous Heat And Water, developed by the Agricultural Research Service of the U.S. Department of Agriculture). The evaluation was directed primarily at examining their algorithms for simulating the energy balance at the land surface. Our intent was to compare simulated soil temperature, soil heat flux, and net radiation with field measurements for each of the three surface types and canopy conditions.

Input data were prepared for each of the three sampling periods in 1992 (March 19-28, April 10-21, and May 8-14) and simulations were run by Mark Wigmosta with the help of Jim Miltz, a high school physics teacher involved in DOE's Teacher Research Associate program. Initial simulations have used wind speed, air temperature, and relative humidity

from the HMS. Final results will include values of these inputs from the eddy correlation data. The 1.5 m soil temperature from the nearby Field Lysimeter Test Facility was used as the lower soil temperature for boundary conditions.

Simulations have been completed for bare soil and sagebrush surface types. Model calibration was achieved by adjusting the soil thermal conductivity, and there is good agreement between observations of the bare soil surface and predicted values. The agreement is not as good between the predicted soil surface under the sagebrush canopy with near-surface thermocouples placed under the sagebrush canopy. Here, there is a general under-prediction of the lower soil temperature. This may be corrected by adjusting the Leaf Area Index (LAI) which controls the amount of radiation reaching the soil surface. This adjustment in LAI is further supported by the current model predictions of higher leaf temperature as compared to measured leaf temperatures.

Future directions for research in this area should include the investigation of responses of the models to stomatal resistance, LAI, soil thermal conductivity, and bulk canopy resistance. The goal of the modeling effort has been to predict values of soil heat storage, soil heat flux, and net radiation. All three of these variables were measured for the three different canopy conditions. We recommend for future work that they be composited based on the area occupied by each cover type and compared to a simulation using composited input data. In addition, the energy balance predicted by these simulations could be compared to the total flux measured by the eddy correlation flux station and to the soil heat flux/storage values measured by the energy balance stations.

Remote Sensing of the Lower Atmosphere

Since October 1993, PNL has operated a 915-MHz wind profiling radar with radio acoustic sounding system (RASS) capability at the HMS. This system is able to provide

nearly continuous vector wind profiles to heights exceeding 6 km and hourly temperature profiles to heights as large as 1 km. Such a system is important to the objectives of IBSEPAC because it provides a means to at least partially measure the larger-scale circulations that interact with the surface fluxes as well as the possibility of obtaining profiles of turbulence fluxes related to the surface energy balance. Because of this system's potential value to the IBSEPAC project (and the ASCOT program in general), we directed some of the IBSEPAC resources to evaluating the capabilities of this system.

In FY 1993, we began a systematic comparison of the wind profiler/RASS's wind vector and temperature measurements with those from the 122-m tower at the HMS, which was located about 500 m away. Instruments at the top of the tower are within the lowest range gate of the radar, providing as direct a comparison as is possible between such different measurement techniques. Additional information from a phased array acoustic sounding system were also used in the comparison. The analysis of data collected for nearly a month in April 1993 was completed in 1994, and the results were presented at an international symposium in Hamburg, Germany, in September. In general, the comparison showed that the profiler's accuracy for mean wind and temperature measurements in the relatively difficult dry climate of the Hanford Site was at least as good as that found for profilers operated in more favorable environments. The primary effect of the dry conditions on radar performance appears to be a loss of altitude co, rather than a loss of accuracy.

In addition to the measurement of mean values of atmospheric variables, the wind profiler/RASS is capable, in principle, of measuring profiles of turbulence fluxes in the lower atmosphere. These fluxes are representative of larger areas than flux measurements made at the surface, and good flux profiles allow the measurement of diagnostic physical balances that are not otherwise possible. Measurements

made during 1993 suggested that the profiler might be able to measure these fluxes over usefully short averaging periods. As a result, a series of measurements was made during the spring and summer of 1994 in order to compare momentum fluxes measured from the profiler with simultaneous momentum fluxes obtained using standard eddy correlation sensors mounted on the HMS tower. These measurements confirmed that the profiler can indeed measure momentum flux profiles over periods as short as two hours, thus opening new uses of the wind profiler/RASS for diagnosing atmospheric circulations. Results of this work were also reported at the international symposium in Hamburg.

One of the fundamental questions remaining in boundary layer meteorology is how one determines a representative value of heat, moisture, and momentum exchange between the surface and the atmosphere when the surface has significant variations in temperature, moisture, or elevation. To assist in addressing this issue, we acquired a laser scintillometer in 1994. This remote sensing system was manufactured for PNL by the National Oceanographic and Atmospheric Administration's Wave Propagation Laboratory in Boulder, Colorado. It has the unique capability of measuring heat and momentum fluxes near the surface and over a path as long as 600 m. This provides a significant new opportunity to assess how the fluxes from individual surface types described above combine to form a total flux over an area. Unfortunately, the delivery of the system came too late in FY 1994 for it to be integrated into the other tasks and objectives of the project. Because of its general usefulness, it will be evaluated and used in future boundary layer projects.

Post-Doctoral Support

Dr. Shiyuan Zhong received her Ph.D. in meteorology at Iowa State University in the

summer of 1992. She joined PNL as a post-doctoral associate through the Northwest Organization of Colleges and Universities for Science in September 1992. IBSEPAC continued to share the cost of her appointment with another DOE research project at PNL in FY 1994. Dr. Zhong has now become a member of the PNL staff.

Goals for 1995

Because of programmatic changes within DOE, 1994 was the final year of the IBSEPAC project.

IBSEPAC Publications during FY 1994

Hubbe, J. M., J. M. Downs, R. R. Kirkham, and W. J. Shaw. 1994. "Surface-Layer Response over Mixed Shrub-Steppe Canopy During Springtime." Extended abstract in preprint volume. Am. Meteor. Soc. 21st Conf. on Agric. and Forest Meteor., March 7-10, 1994, San Diego, pp. 319-322.

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Zhong, S., W. J. Shaw, and J. M. Hubbe. 1994. "An Evaluation of 915-Mhz Radar Wind Profiler/RASS by Tower and Sodar Measurements." Extended abstract in preprint volume, *3rd Internat. Symp. on Tropospheric Profiling: Needs and Technologies*, Hamburg, Germany, August 30-September 2, 1994, pp. 289-291.

Coupling/Decoupling of Synoptic and Valley Circulations

Principal Investigator: C. D. Whiteman

The objective of the Coupling/Decoupling of Synoptic and Valley Circulations (DECUP) research program is to develop an improved understanding of the physical mechanisms leading to interactions between thermally driven local wind systems and the ambient flows.

Current program goals are to gain a better understanding of the basic physics, driving forces, and interactions of thermally developed complex terrain circulations of different scales. These complicated interactions represent significant challenges being met with an integrated program of new field investigations, data analysis of past complex terrain experiments, and mathematical modeling of relevant physical mechanisms. Field investigations make use of remote and in situ atmospheric sounding devices, radiation and energy budget systems, tracer samplers and basic meteorological sensors. Data sets come from the DOE Atmospheric Studies in Complex Terrain (ASCOT) program and other complex terrain experiments; simulations come from a variety of meteorological models, from simple thermodynamic to full-physics numerical models.

This project is conducted as an integral part of the ASCOT multi-laboratory program and is closely coordinated with two other ASCOT programs at PNL, the Atmospheric Diffusion in Complex Terrain (ADICT) and the Direct Simulation of Atmospheric Turbulence (DSAT) programs.

FY 1994 Accomplishments

FY 1994 activities are described in the following subsections.

Solar Semidiurnal Tides

During FY 1994, while developing a climatological method for investigating the diurnal mountain-plain circulation system in the Rocky Mountains, we discovered a semidiurnal mountain wind system that produces circulations identifiable in long-term records. Our further investigation has led to the conclusion that the mountain wind system is part of a global semidiurnal tidal wind system produced by absorption of solar radiation by ozone in the upper stratosphere. Using additional 915-MHz radar profiler records, we have now confirmed that this tidal wind system occurs over the southern and central Rocky Mountains. We presume that the wind system will be apparent in radar profiler records over the entire globe. The circulations may play a significant role in the formation of clouds, fogs, and precipitation in the tropics and subtropics and in areas where

the tides are enhanced by mountain or coastline interactions. Many observational details of this circulation are, as yet, unknown. Of special interest is their seasonal and altitudinal variations and their global phases and amplitudes. We prepared a conference paper on these results and are now writing a journal article.

Pressure-Driven Channeling in the Tennessee Valley

In FY 1994, we published a climatological method for investigating the coupling and decoupling of valley and overlying synoptic-scale circulations. The method relies on the recognition of patterns in wind direction joint frequency distributions and was illustrated for the Tennessee Valley, the site of a 1991 ASCOT field experiment. The method showed that winds in this valley are driven primarily by the along-valley component of the synoptic-scale pressure gradient. We learned that the Tennessee Valley Authority will be using our method to improve its forecasting of Tennessee Valley winds. The Authority has also offered

access to special data sets that may prove useful in extending our understanding of wind fields in this valley.

Stagnations and Recirculations

In FY 1994, in cooperation with PNL's ADICT program, we published a journal article that provides a new approach to defining critical air pollutant transport properties such as stagnation, ventilation, and recirculation. These transport properties were defined mathematically, and numerical calculations of the properties were illustrated using wind data time series from towers and radar wind profilers located in the southwestern United States. The method is suitable for quantifying important aspects of the dispersion meteorology of a region, and can be used to prepare comparative air pollution dispersion climatologies for different regions of the U.S.

Dispersion Meteorology

The standard deviation of wind direction, commonly called sigma theta, is related to horizontal turbulent diffusion in the atmosphere and has been widely used in dispersion calculations. An unusual set of new measurements of sigma theta has recently become available for an area of complex terrain in the Colorado Plateaus Basin in Arizona and Utah. This data set includes wintertime data from 13 identical meteorological stations located in widely varying terrain throughout a large basin, and analyses of these data are under way as part of a joint effort with Drs. K. J. Allwine of PNL and R. K. Hauser of California State University at Chico. Dr. Hauser spent a sabbatical leave at PNL during 1994.

Initial analyses show distinct relationships between the elevation and exposure of the wind stations and the statistics of the hourly sigma theta values. At ridge-top sites hourly distributions have small standard deviations and positive kurtosis. Open exposure sites that experience channeled flows show the greatest positive skewness and kurtosis. Sheltered-exposure and

basin locations exhibit large standard deviations, the smallest skewness, and negative kurtosis. Diurnal effects on wind direction variability are most evident where local terrain contrast is most extreme and are difficult to detect, or are absent, at high-elevation ridge-top sites. There is a tendency for the product of the hourly sigma theta and the hour-a vector wind speed to yield a site-specific empirical constant, which exhibits a dependence on elevation, site exposure, stability and strength of the overlying flow. We are investigating the possibility that such relationships can be used to map the expected wind direction variability in complex terrain, as this would make an important contribution to the understanding of turbulent dispersion of air pollutants in complex terrain areas. Initial results from these analyses were presented in a conference paper in early FY 1994, and a further analysis of the effects of topography and averaging time was presented at an ASCOT Science Team Meeting in February 1994. A journal article is being prepared.

Atmospheric Energy Budgets Using Wind Profiler/RASS Networks

The use of networks of radar wind profilers and remote acoustic sounding systems for computing atmospheric heat budgets has been evaluated in a collaborative research project with Dr. Markus Furger of Switzerland's Paul Scherrer Institute (a visiting scientist at PNL in FY 1993) and Dr. James Wilczak of NOAA's Environmental Technology Laboratory (ETL). Such heat budgets are useful in understanding the energetics of local flows and boundary layer processes. The work was jointly supported by the DOE ASCOT and Atmospheric Radiation Measurement (ARM) programs, and was focused on the application of new remote wind and temperature sensing technologies for boundary layer meteorological investigations. The research involved the determination of the effects of typical wind and temperature

measurement errors on the atmospheric heat budget equation using a Monte Carlo-type model.

In FY 1994, the research was presented at an international conference, and a journal article was accepted. The simulations show that individual terms of the budget equation are not equally sensitive to measurement errors and are dependent on atmospheric stability, mean wind speed, averaging times triangle size, baroclinity, and wind divergence. Under favorable conditions, reasonably accurate estimates of each of the terms of the atmospheric heat budget (excluding radiation) can be derived from measurements obtained with a triangular array of ground-based remote sensors. They provide nearly continuous measurements of the advection term so often neglected in atmospheric boundary layer studies. The simulations show that significant improvements in the evaluation of the heat budget equation would be produced if temperature measurement accuracy could be improved. Such improvements appear to be possible by simply increasing the frequency of RASS observations.

Front Range Studies

The DECUP program participated in a multilaboratory ASCOT intensive experiment in Colorado's Front Range from August 1993 through October 1993. We deployed a radar profiler/RASS, two Doppler sodars, and standard weather station equipment as part of this experiment. The continuous data stream from

these instruments is being archived at Argonne National Laboratory. The 1993 ASCOT experiment focused on dispersion meteorology in the neighborhood of DOE's Rocky Flats Plant, and was designed to investigate mountain-plain circulations and tributary flows at the mountain-plain interface. The original schedule for radar profiler/RASS operation was extended through February 1994 to take advantage of opportunities to use related data sets being collected by NOAA.

Other Collaborations

Scientists in European countries are initiating a new research program concerning the effects of mountains on mesoscale meteorological processes. This program, termed the Mesoscale Alpine Program (MAP), is a follow-on to the successful Alpine Experiment (ALPEX), conducted in 1982. In FY 1994, Dr. Whiteman, with support from the ASCOT program, was on a short-term assignment to the Paul Scherrer Institute and the University of Bern. During this assignment, he assisted in planning the MAP program and field experiments, and coordinated the ASCOT and MAP programs.

Future Work

This research program will end in FY 1994. Our contributions to the multilaboratory ASCOT program will continue over the 3 three years, however, through acceptance of several successful competitive proposals.

Climate
Research

Climate Research

Climate change research at PNL is aimed at reducing uncertainties in the fundamental processes that control climate systems that currently prevent accurate predictions of climate change and its effects. PNL is responsible for coordinating and integrating the field and laboratory measurement programs, modeling studies, and data analysis activities of the Atmospheric Radiation Measurements (ARM) program. The ARM program will increase the reliability of predicting regional and global changes in climate in response to increasing atmospheric concentrations of greenhouse gases including CO₂. Improvements in the treatment of radiative transfer in general circulation models (GCMs) under clear sky, broken cloud, and general overcast conditions and improvements in the parameterization of cloud properties, cloud formation, and cloud maintenance in GCMs are the objectives of the multi-laboratory effort being led by PNL.

In FY 1994, PNL scientists conducted 3 research projects under the ARM program. In the first of these projects, the sensitivity of GCM grid-ad meteorological properties to subgrid-scale variations in surface fluxes and subgrid-scale circulation patterns is being tested in a single column model. In addition, new procedures are being developed for extrapolating local point measurements of sensible and latent heat flux to GCM grid-ad values. In the second project, a new and computationally efficient scheme has been developed for parameterizing stratus cloud microphysics in general circulation models. With better estimation of critical microphysical properties, the optical properties of these clouds can be estimated more confidently. In the last project, a balloon-borne instrument package is being developed for making research-quality measurements of radiative flux divergence profiles in the lowest 1,500 meters of the Earth's atmosphere.

As part of DOE's program to quantify the linkages between changes in atmospheric composition and the temperature of the planet, PNL is studying how clouds and aerosols interact with short- and long-wave radiation to regulate the heating of the planet. Data from a network of surface-based, spectrally-resolved direct and diffuse short-wave radiation sensors and ancillary meteorological sensors will be used to improve the parameterization of the radiative effects of clouds and aerosols.

Research on greenhouse gas emissions continues to improve the reliability of forecasts of emissions of CO₂ and other radiatively active gases. Model development, validation, and uncertainty evaluations depend on improved and expanded data bases, including more definitive information on energy production and consumption practices both in the U.S. and in other key countries. The changing technologies and policies of the United States and other countries are being analyzed to anticipate contributions to future emissions of greenhouse gases and their effects on society, particularly on a regional basis. Finally, improvements are being made in the treatment of the effects of various taxes in the representation of key economic sectors.

In FY 1994, ocean research related to climate change examined air-sea interaction processes, ocean mixed-layer dynamics, and the process of deep convection in the ocean. PNL is working to develop procedures for estimating air-sea gas transport from remote sensors and to improve parameterizations of the dynamics of the surface mixed layer, transport through the thermocline, and the formation of deep water.

The progress described in the articles that follow was supported by the following research projects:

Atmospheric Radiation Measurements Program

- Point-Area Relationships for Global Climate Models
- A Stratiform Cloud Parameterization for General Circulation Models
- Photometric Studies of Clouds from an Atmospheric Radiation Site
- Characterization of Cloud/Aerosol Interactions with Solar and Longwave Radiation
- Second Generation Model
- CO₂ Ocean Research

An Analytical and Modeling Study of the Effects of the Low-Level Jet on Clouds and Radiation at the Southern Great Plains Clouds and Radiation Test Bed

Principal Investigator: S. J. Ghan

Analysis Task

Much of the early effort in FY 1994 involved project planning, especially related to determining the analysis and modeling data needed to successfully complete the project. An experiment design document was prepared, and members of the experiment support team prepared an experiment operations plan specifying data that would be delivered by the Atmospheric Radiation Measurement (ARM) Program. Some organizational problems were experienced that resulted in late delivery of data and, because the project needed significant amounts of "external" data, some data still have not been received.

In the analysis task, the focus was placed on investigating physical mechanisms leading to low-level jets (LLJ), using both climatological and case studies. Work began with an extensive review of the scientific literature and presentation of a literature review seminar. The initial climatological analyses were planned around data from the National Oceanic and Atmospheric Administration's (NOAA) Wind Profiler Demonstration Network (WPDN). Historical data for this network were obtained from Dr. Ray Arritt at Iowa State University. Data from this network of radar wind profilers were provided to Dr. Arritt by the National Climate Data Center (NCDC) in a format called EBUFR. Dr. Arritt had experienced a number of problems in converting these data to NetCDF and ASCII formats. A collaborative

effort between ARM and Dr. Arritt was established to solve these data conversion problems.

Communications with Dr. Jim Wilczak at NOAA also revealed that the WPDN radar-derived wind data suffered from wind direction and speed contamination by migrating birds. The contamination is especially strong at the lower levels of the atmosphere during periods of peak migration, especially at night. Procedures for identifying and rejecting contaminated data have been developed at NOAA, and algorithms for the removal of bird effects from data in real time are just now being installed in NOAA radar wind profilers. The method for removing contaminated data from the historical database requires that radar moments files be available. Dr. Arritt will order these data from NCDC soon and has agreed to collaborate with us in processing the new data.

In the meantime, we identified a 1-month period during mid-summer when the bird contamination problem is minimized and are pursuing case study and climatological analyses of this period using data from 1991 and 1992. We have also found two LLJ cases during the spring 1993 intensive observational period (IOP) at the southern Great Plains site. Bird contamination of the radar wind profilers during these periods will be checked by using 12-hourly rawinsonde data. Analyses are focusing on the temporal and spatial characteristics of the low-level jets with an emphasis on the usefulness of this information in

investigating physical mechanisms, especially when used in conjunction with our mesoscale modeling efforts.

To date, we have developed various programs for converting LLJ data sets from EBUFR and NetCDF formats to standard ASCII files and have also developed graphics routines to display and analyze the data. A major finding from our time series analysis routines is the discovery of significant semi-diurnal atmospheric tidal oscillations over the entire central United States. Other preliminary findings are coming from investigations of the effects of the LLJ on vertically integrated moisture fields over the southern Great Plains using combined satellite-borne and ground-based remote sensors. Findings of our analyses to date are reported below.

Case Studies During the CART IOPs

We have now completed an analysis of daily data from the June 1993 CART IOP. Two cases with strong LLJ signature (June 15-17 and June 22-23, 1993) were found. In these cases, southerly winds at a number of stations reached 18-20 m/s in the layer between 600-800 m above ground level and decreased rapidly with height to only 8-10 m/s at 2000 m. Meanwhile, the temperature profile indicated that the top of the surface inversion layer was at about 600 m AGL, which corresponded well with the height of the jet maximum. During the period June 15-17, 1992, a strong LLJ dominated at more than 20 stations in the mid-western United States. A jet core extended from southwest (Winnfield, Louisiana; Palestine, Texas; and Jayton, Texas) to northeast (Lathrop, Missouri; Fairbury, Nebraska), with the strongest wind near Lamont, Oklahoma. The spatial and temporal distribution of the LLJ is complicated. Some stations exhibited a very strong inertial oscillation based

on wind hodograph analysis (e.g., at Jorton, Texas; Purcell, Oklahoma), while other stations did not have a clear inertial oscillation (e.g., at Granada, Colorado; and McCook, Nebraska). This preliminary analysis suggested that the inertial oscillation induced by the sudden cessation of turbulent mixing in the lower boundary may be a major factor in producing LLJs for some cases, but not all. More investigations are underway to understand the observed spatial and temporal distributions.

Monthly and Seasonal Data Analysis - Climatological Study

Seasonal characteristics of the LLJ are being analyzed using two warm season sets of WPDN data, and the results are being compared to GCM outputs. Twelve-hour monthly mean nighttime winds at most stations for July showed a clear jet of about 10 m/s between 500-1000 m. Early warm season nocturnal monthly mean data indicated two low-level wind maxima at some stations, which possibly may be the result of bird contamination. Comparison of observed and global climate model (GCM)-predicted monthly and seasonal characteristics is currently underway.

Semidiurnal Tidal Oscillations

Time series analysis of wintertime WPDN data has identified semidiurnal tidal wind oscillations above the central United States. These wind systems had been predicted by global climate and upper atmospheric models but have never been reported from radar profiler data. The observed wind systems are stronger than predicted by models, but can be seen only in long-term climatological records composited over periods of 30-40 days or more. The tidal wind speeds increase with height through the troposphere attaining speeds of about 1 m/s in mid-troposphere. In conjunction with another

DOE research program we are investigating the possible influence of these wind systems and related divergence fields on fog, cloud and precipitation climatologies and their possible direct effects on the LLJ.

Satellite and Ground-Based Remote Sensing of Atmospheric Moisture

To assess the contribution of the LLJ to moisture fluxes over the southern Great Plains, the spatial distribution of moisture must be measured for the entire region at frequent (e.g., hourly) intervals. This is complicated by the lack of moisture data at this frequency, because rawinsondes are launched at 12-hour intervals.

Because the jet is a near-surface phenomenon, and because most of the atmospheric water vapor is located within the lowest 2-3 km, column-integrated moisture is expected to be representative of moisture carried at low levels by the LLJ.

To overcome the lack of moisture information and investigate the role of the LLJ on moisture transport in the southern Great Plains, we have implemented an algorithm developed by Chesters et al. (1983). This algorithm uses the "split window" channels of the GOES/VAS satellite at 11 and 12 μm constrained with surface-based measurements to estimate the spatial distribution of column-integrated water vapor. Whereas Chesters et al. used the twice-daily NWS soundings to provide the column-integrated vapor necessary to constrain the hourly GOES/VAS imagery, we are using the continuous measurements of integrated vapor provided by the CART microwave radiometers. In this way we can more closely match the temporal and spatial resolution of the satellite (e.g., zenith-viewing instantaneous values at hourly intervals rather than time and space-integrated values over the wandering trajectory of the balloon at 12-hour intervals). We expect

this to result in more accurate estimates of the integrated water vapor amount (Chesters et al. report 1 cm RMS accuracy), which is necessary for the moisture flux calculations we will perform to study the LLJ.

Microwave radiometer and GOES/VAS data have been acquired from ARM for April and June 1994 to support this analysis.

Mesoscale Modeling Task

A series of idealized simulations have been conducted using the Regional Atmospheric Modeling Systems (RAMS). The objective of these modeling efforts was to gain further understanding of the physical mechanisms that lead to the formation of the Great Plains LLJ and the sensitivity of the jet characteristics to model parameterizations.

We began our simulations by using a two-dimensional domain that approximates a vertical cross section of the Great Plains parallel to the Kansas-Oklahoma border. The two-dimensional domain allows very fine resolution in the vertical to better resolve the vertical structure of the jet and examine the sensitivity of the jet characteristics to the model vertical resolution. It also allows a detailed sensitivity study of the jet properties to the model parameterizations. As discussed in Bonner (1968), nearly all spring and summer LLJs over the Great Plains region occur during periods of predominantly southerly and southwesterly winds. A typical spring synoptic situation of moderate southerly wind was used to initialize the model. Each of the simulations begins at local sunrise and is numerically integrated with a time step of 60 seconds for a 24-hour period.

Holton (1967) indicated that thermally driven flows across the gently sloping Great Plains may create ageostrophic wind components, which, after inertial rotation of the wind at night, result in jets with wind speed

comparable to observations. The effect of sloped terrain on the LLJ was examined by comparing the results from simulations over a flat surface and those over an assumed terrain slopping from east to west similar to the Great Plains. The existence of the slope increased the maximum wind from 20% supergeostrophic to about 40%, which is considerably less than the 140% increase predicted by Fast and McCorcle (1990), but comparable with the results by Clark (1987).

The inertial oscillation theory of the LLJ implies that the ageostrophic wind component will rotate with a period proportional to $2\pi/f$, with f the Coriolis parameter, which depends only on latitude. According to this hypothesis, the period of the inertial oscillation should decrease, or the time of the jet maximum should occur earlier at more northerly locations. The model predicts that the jet maximum occurs closer to 0600 LST at 25°N , and closer to 0200 LST at 45°N . The supergeostrophic wind is stronger at low latitude than at higher latitude. The large amplitude of the jet at low latitude results from a stronger upslope component that reaches its maximum at 1800 LST near sunset. But at progressively higher latitudes, the maximum upslope component is weaker in response to weaker temperature gradient because of less heating along the slope.

Detailed sensitivity study of the jet to model parameterizations were also conducted. LLJ was found to be very sensitive to model vertical resolution in the lowest 1 km of the boundary layer. Coarse resolution resulted in a weaker jet at higher level than fine resolutions. But the timing of the maximum jet speed has little to do with the model vertical resolution. The model turbulence parameterization schemes (a deformation-based scheme and Mellor-Yamada 2.5 level closure) show little

effect on the jet characteristics except some impact on the broadness of the jet. On the other hand, the surface characteristics such as soil moisture and vegetation cover show large impact on the properties of the jet.

A three-dimensional real case simulation is currently underway. The case is chosen from the NCAR 93 June IOP. Data analysis shows a well-defined LLJ occurred over most of the Great Plains region including the CART site for 3 days. The real data simulation would allow us to compare the model results with detailed observations. It will also allow us to examine the three-dimensional effects of topography and synoptic forcing that could not be studied by the two-dimensional configurations.

Global Climate Modeling Task

During FY 1994, the global climate modeling task focused on determining if or to what degree the LLJ climatology and its impact on clouds and precipitation are being captured by current GCMs. Our hypothesis is that current GCMs do not simulate the LLJ, so that a parameterization will be required. This first task evaluates the need for a parameterization.

To assess the simulation of the LLJ, we use the LLJ criteria 1 of Bonner (1968). We first applied Bonner's criteria to the winds simulated by the European Center for Medium-Range Weather Forecasts (ECMWF) model (T42 resolution) driven by sea-surface temperatures observed during the AMIP period 1980-1989. The simulation was performed by the Program for Climate Model Diagnoses and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory. Our initial analysis focused on the simulation for June 1980. Figure 1 shows the spatial distribution of simulated LLJ frequency, using 6-hour samples. It is remarkably similar to that estimated from observations (Bonner 1968), with the maximum frequency of about

50% occurring over Texas and Oklahoma, and frequencies of less than 5% over most of the eastern and western United States. Helfand and Schubert (1995) found a very similar distribution of the LLJ frequency simulated by the GEOS-1 model. The intensity of the mean simulated LLJ is somewhat weaker than observed during 16 summer "jet" days (Bonner 1968), but the difference may be attributed to the selective sampling in the observations.

We are frankly surprised at the ability of the ECMWF and GEOS-1 models to simulate the LLJ, because to our knowledge these models have not been tuned to simulate the LLJ. This suggests that a parameterization of the LLJ itself may not be required, provided the simulation of the LLJ is robust. We have therefore asked PCMDI to send us data for other months and years simulated by the ECMWF model, and have begun a series of experiments with the NCAR community climate model (CCM2) to evaluate the ability of the CCM2 to simulate the LLJ. Preliminary experiments with CCM2 indicate that at R15 resolution the simulation of the LLJ by the CCM2 is very poor, but at T42 resolution the distribution of the simulated LLJ frequency is comparable to that simulated by the ECMWF and GEOS-1 models. This suggests that the simulation of the LLJ may be robust with respect to model physics, but requires a horizontal resolution of T42 or finer. However, longer simulations and additional experiments with different model physics are needed to solidify this conclusion.

If we find that GCMs can simulate the LLJ, then the LLJ itself need not be parameterized. However, the influence of the LLJ on clouds and precipitation may still need to be parameterized. To evaluate the need for parameterizing this influence, we have examined the

convective precipitation rate simulated by the ECMWF model. Convective precipitation is strongly related to the occurrence of thunderstorms. Hering and Borden (1962) and Pitchford and London (1962) have shown that associated with the LLJ is a nocturnal maximum in convective activity over the central United States. Thus, one means of evaluating the simulation of the influence of the LLJ on clouds and precipitation is to examine the diurnal cycle of the simulated convective precipitation. We have found that although the ECMWF successfully simulates the LLJ, it fails to simulate the nocturnal maximum in convective precipitation in the central United States, at least for the one month of June data that we have. If this conclusion holds for other years and for other models, the influence of the LLJ on convective clouds and precipitation will have to be parameterized.

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A Stratiform Cloud Parameterization for General Circulation Models

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Co-Investigators: L. R. Leung, Q. Hu, J. E. Penner^(a), C. C. Chuang^(a), and, J. McCaa^(b)

The crude treatment of clouds in General Circulation Models (GCMs) is widely recognized as a major limitation in the application of these models to predictions of global climate change. The purpose of this project is to develop a stratiform cloud parameterization for GCMs that expresses clouds in terms of bulk microphysical properties and their subgrid variability. Precipitating cloud species will be distinguished from non-precipitating species, and the liquid phase will be distinguished from the ice phase. The size of the non-precipitating cloud species (which influences both the cloud radiative properties and the conversion of non-precipitating cloud species to precipitating species) will be determined by predicting both the mass and number of each species. The Atmospheric Radiation Measurement (ARM) Clouds and Radiation Testbed (CART) facility will be used to evaluate the parameterization of clouds and their radiative impact.

FY 1994 Accomplishments

In previous years we demonstrated the feasibility of applying to stratiform clouds a bulk cloud microphysics parameterization designed for cumulus clouds (Ghan and Easter 1992), developed a cloud droplet nucleation parameterization so that droplet number can be related to aerosol concentration (Ghan et al. 1993, 1994), developed a formalism for treating subgrid variations in clouds and cloud processes, and applied a bulk cloud microphysics parameterization to a GCM. Here we review our FY 1994 objectives, our progress toward those objectives, and our plans for future work.

Objectives for FY 1994 were the following:

- complete the representation of subgrid variations in cloud microphysics
- apply the cloud parameterization to a GCM

- apply the droplet nucleation parameterization to the GCM
- evaluate the cloud parameterization when applied to ARM CART sites in a column model.

Subgrid Cloud Parameterization

The coarse resolution of global models is clearly inadequate to resolve the climatically important features of most clouds and cloud systems. Subgrid variations in cloud properties and cloud processes must therefore be represented in global models. We have developed a statistical formalism that expresses subgrid scale variations in cloud microphysical properties in terms of idealized probability distributions. Although subgrid variations as a result of a variety of processes could, in principle, be applied to the formalism, we are focusing on

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subgrid variability as a result of local turbulence. We have applied the Mellor-Yamada level 2.5 turbulence closure scheme to the liquid-phase cloud variables in the single-column model. During FY 1994 we applied the parameterization to rain as well as cloud water. Variance and covariance of temperature, cloud water, and rain are now predicted. By assuming idealized probability distributions for the cloud variables, the influence of subgrid cloud variations on cloud processes (autoconversion and collection) is represented. We introduced joint probability distributions for cloud water and rain to treat the subgrid dependence of collection on cloud water and rain. We have performed some simple test simulations with the single column model, but are awaiting the distribution of ASTEX data before we evaluate the parameterization.

Application to a GCM

We have applied the Colorado State University bulk cloud microphysics parameterization (Cotton et al. 1986) to the National Center for Atmospheric Research (NCAR) community climate model (CCM2). The scheme predicts cloud liquid water, cloud ice, and ice number. We have replaced the CCM2 prognostic variables temperature and water vapor with condensation-conserved variables so that cloud water need not be predicted separately; cloud water is diagnosed from the condensation-conserved variables and the constraint that water vapor pressure never exceeds saturation vapor pressure with respect to liquid water. We adopted the approximations of Ghan and Easter (1992) to permit the use of much longer microphysical time steps and found that, given the weak vertical velocities resolved by the global climate model (GCM), microphysical time steps of 20 minutes and

800 seconds are accurate at R15 and T42 resolutions, respectively. Subgrid variations in clouds and cloud processes are not yet treated.

We have found that the simulated cloud radiative forcing can be rather sensitive to the parameterization of cumulus clouds in the GCM. Cumulus clouds detrain condensed water near cloud top, and hence, serve as a source of condensed water for the simulated stratiform clouds. The condensed water influences the cloud radiative properties, and hence, the planetary radiation balance. How much condensed water is detrained depends on the precipitation efficiency of the cumulus clouds, which is parameterized in the NCAR CCM2 model in terms of an "overshoot" parameter. We have found that plausible changes in the precipitation efficiency can yield differences in the planetary radiation balance as large as 20 W/m². Table 1 summarizes the simulated and observed global mean cloud radiative forcing for January and July. The CCM2 has been run at T42 resolution for 1 year; the observations span 3 years. Two simulations have been performed: one with the standard treatment of cumulus convection in CCM2, in which the minimum value of the overshoot parameter is 0.1, the other with a minimum overshoot parameter of 0.0. The simulation that permits smaller values of the overshoot parameter yields a cloud radiative forcing that is closer to that observed, by about 10 W/m². Figure 1 shows the zonal mean distributions of simulated and observed cloud radiative forcing for January and July. The spatial structure of both the longwave and the shortwave cloud forcing is simulated quite well. However, biases in the simulated longwave cloud forcing are evident in middle and polar latitudes in both January and July.

FIGURE 1: Zonal Mean Simulated (dashed line) and Observed (solid line) Longwave (left) and Shortwave (right) Cloud Radiative Forcing Ad over January (top) and July (bottom), as Functions of Latitude

TABLE 1. Cloud Radiative Forcing (W/m ²)		
	January	July
Longwave		
Observed	26.4	21.9
Standard convection	40.4	42.7
Modified convection	36.1	36.8
Shortwave		
Observed	-50.8	-44.4
Standard convection	-43.0	-43.6
Modified convection	-51.8	-49.1

According to the droplet nucleation parameterization we have developed, the number nucleated is a nonlinear function of updraft velocity. Because global models do not explicitly resolve updraft velocities, subgrid variations in vertical velocity must be parameterized before the droplet nucleation parameterization can be applied to the GCM. As a first step toward the application of our subgrid parameterization to a GCM, we have introduced the Mellor-Yamada level 2.5 turbulence closure scheme in CCM2. The scheme predicts turbulence kinetic energy (which can be related to updraft velocity) as well as subgrid variance in temperature and cloud water. The droplet nucleation parameterization is now being applied to the CCM2 so that droplet number can be predicted and related to aerosol concentration.

Evaluation

An essential task in the development of the cloud parameterization is its verification. Although some aspects of verification will be achieved using climatological simulations with a GCM, more control is possible by applying the cloud parameterization to forecast experiments in the field. During FY 1994 we drove our single column cloud model with winds analyzed by the MAPS system, and compared

simulated surface irradiance and column liquid water with observations at the ARM CART site in Oklahoma. We found the results were sensitive not only to the analyzed vertical velocity, but also to assumptions about the upstream cloud water concentration. Under strongly advective conditions, the assumption of no upstream cloud water yields a simulated column liquid water that is 30% less than under the assumption that upstream liquid water equals the liquid water at the center of the column model. This suggests that under strongly advective conditions, the lateral boundary conditions on clouds control the simulated cloud, so that under such conditions a single-column model is not a useful tool for evaluating a cloud parameterization. Under strongly advective conditions cloud parameterizations can only be evaluated using multi-dimensional models spanning a domain large enough that the lateral boundary conditions are unimportant. Typically, domains of several thousand kilometers, much larger than the size of single GCM grid cell, are required.

We have therefore applied our cloud parameterization to a multi-dimensional regional circulation model, namely the Penn State/NCAR Mesoscale Model (MM5). The model is driven by observed lateral boundary conditions for winds, temperature, pressure, and water vapor. To reduce the influence of errors arising from the amplification of dynamical instabilities in the simulation interior, we have applied a simple Newtonian nudging toward observed winds and temperature in the interior of the domain. Figure 2 compares the simulated outgoing solar centered on the CART site in Oklahoma. Two simulations are shown, one with and one without nudging, to illustrate the value of nudging in the simulation. Clearly the nudging significantly improves the simulated clouds and radiation balance.

GOES Visible, 7 Nov 1987 19:31

MMZIGGY Outgoing Solar, 7 Nov 1987 20:00, With nudging

MMZIGGY Outgoing Solar, 7 Nov 1987 20:00, No nudging

FIGURE 2: GOES Visible Image for 19:31Z November 7, 1987 (top); Outgoing Solar Radiation Simulated at 20:00Z November 7, 1987, with Nudging (middle) and Without Nudging (bottom)

Future Work

The following tasks are planned for FY 1995:

- complete a three-year global simulation using the cloud parameterization in NCAR CCM2 with prescribed droplet number and without subgrid variability. Prepare a journal article comparing the simulated cloud, precipitation, and radiation fields with surface and satellite observations.
- extend the subgrid parameterization to treat variability in droplet number. Prepare a journal article using ASTEX data to evaluate the representation of subgrid variations in warm cloud microphysics in the single column model.
- complete the application of the warm cloud subgrid variability treatment in the NCAR CCM2. Perform a 3-year simulation with prescribed droplet number but predicted variability in cloud water and rain. Prepare a journal article comparing the simulated cloud, precipitation, and radiation fields with surface and satellite observations.

- perform preliminary experiments with predicted droplet number in the NCAR CCM2. In preparation for optimal nudging experiments, derive the adjoint of the cloud microphysics parameterization.

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Characterization of Cloud/Aerosol Interactions with Solar and Longwave Radiation

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The purpose of the Quantitative Links component of DOE's Expanded Carbon Dioxide (CO₂) Research Program is to quantify linkages between changes in atmospheric composition and the temperature of the planet. Although significant efforts have been made to understand expected changes in climate that may result from an increase in CO₂ and other greenhouse gases, there has also been a growing recognition of the role that clouds and aerosols play in regulating the planetary energy balance resulting from their interaction with incoming solar radiation and outgoing infrared radiation. Clouds are important because at any given time they mask about half of the earth's surface, substantially modifying reflected solar radiation and moderating the emission of long-wave radiation. Aerosols affect climate both directly, through reflection of solar radiation away from the planet, and indirectly, by acting as condensation nuclei for the formation of clouds, which may alter the structure and optical properties of clouds. Better understanding of these climatically important and sometimes opposing effects is needed for improving parameterizations of radiative transfer in cloudy, turbid atmospheres for use in General Circulation Models (GCMs) and other related models.

The objective of the Network-Based Solar and Meteorological Characterization of Cloud-Radiation Interaction in Global Climate Modeling Project is to investigate how clouds and aerosols interact with long- and short-wave radiation to regulate heating the planet. To understand how cloud- and aerosol-induced radiative effects vary in time, with cloud structure and type, for a mid-latitude continental area, a nine-station network (the Quantitative Links Network) was established in the midwestern and eastern United States. Each station is equipped with a uniquely designed multifilter rotating shadow-band radiometer (MFRSR) to measure direct normal, diffuse horizontal, and global horizontal irradiance in six narrow-wavelength spectral bands. An additional measurement, using an unfiltered silicon photodiode, approximates total short-wave irradiance. Measurements of downwelling long-wave radiation are made with a pyrgeometer. Local ground albedo measurements are made primarily to identify the presence of snow. Standard meteorological measurements of relative humidity, temperature, and rainfall supplement the radiation measurements. A major advantage of the experimental design for this project is that each measurement station can operate independently and unattended, with only periodic maintenance checks by site operators. The data are retrieved automatically using telephone and modem through a central data archiving computer system at PNL. This study is currently in its last year of a 5-year research period.

FY 1994 Results

Specific objectives accomplished during FY 1994 were 1) operation and maintenance of the field sites, including the diagnosis and

correction of malfunctions; 2) data collection and archival; 3) application of previously developed data analysis techniques to interpret

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the measurements; and 4) reporting of findings at scientific meetings and in journals.

The project is a cooperative effort between PNL and the Atmospheric Sciences Research Center (ASRC) of the State University of New York at Albany (SUNY-Albany).

Instrumentation

The primary instrument at each site is the MFRSR. It was developed jointly at PNL and SUNY-Albany. The MFRSR is described in a previous annual report (Laulainen et al. 1992); hence, only the essential features are presented here. The MFRSR measures total horizontal and diffuse horizontal irradiance in six narrow spectral intervals and in one broad band that is used to measure total short-wave irradiance. Direct normal irradiance is calculated for each spectral channel by subtracting the diffuse irradiance from the total horizontal irradiance and dividing by the cosine of the solar-zenith angle. A microprocessor on the main circuit board controls the band motion, acquires data from the MFRSR and auxiliary instruments, and communicates with the host computers at PNL and SUNY-Albany via modem. Data acquisition, processing, and analysis are performed on Sun SparcStation IPC systems and graphics terminals. Further discussion on instrument calibrations and performance tests of the MFRSR may be found in Harrison et al. (1994).

Site Operation and Maintenance

The installation of instruments at the nine sites of the Quantitative Links Network (QLN) was completed in fall 1991. A description of the sites may be found in Laulainen et al. (1993). During FY 1994, the principal maintenance problem was caused by lightning strokes in the vicinity of the instruments. The most severe, knocked out the Bondville

(Illinois) unit again for several months.

Another problem was discovered during the maintenance and calibration visits. It was found that some units were leaking water around the diffuser, because the material used for the diffuser/integrating cavity had shrunk, and the press-fit seal was no longer impervious to water leakage. Severe degradation to the MFRSR detector head and electronics was sustained in two units. Corrective action is being taken to remachine and seal the heads.

Data Management

The goals of the data management task are to acquire a complete and reliable atmospheric radiation data set, and provide it to principal investigators and the scientific community in an easy-to-use format. PNL is responsible for primary data collection and management. SUNY-Albany provides backup data collections three times per week. The QLN generates approximately 90,000 bytes of solar and atmospheric radiation and meteorological data each day. The data are transferred nearly daily from each of nine QLN stations to a host computer at PNL. Data management software interprets the data files and converts all the data to character-format files that contain one complete day of data per station. These day-files are in a generic form, readable by any computer, and are easily ingested by the "S-PLUS" statistical analysis software package currently used at PNL and ASRC. ASRC provides the correct mathematical functions for converting the raw output into calibrated engineering units. The data are then permanently archived at PNL. An important analysis tool, an objective automated algorithm for the retrieval of optical depth and outside-the-atmosphere intensity for each wavelength channel (Harrison and Michalsky 1994), was exercised in an operational mode, not only for the QLN data, but for

data from the ARM southern Great Plains site as well. This tool, which we frequently refer to as the objective Langley analysis technique, is based on the assumption that the measured direct irradiance for each of the five filters we use for aerosol optical depth retrieval follows the Bouguer-Lambert-Beer law,

$$I = I_0 \cdot \exp(-\tau \cdot m) \quad (1)$$

where

I = measured direct irradiance
 I_0 = outside-the-atmosphere direct irradiance
 τ = total optical depth
 m = air mass relative to the zenith direction.

For constant τ and I_0 , least-squares regression of $\ln(I)$ versus m produces a linear plot with a negative slope of τ and an intercept of $\ln(I_0)$, the so-called Langley method.

Data Analysis and Interpretation

In the previous annual report (Laulainen et al. 1994a), time-series data were presented showing the effect of volcanic eruptions on aerosol optical depth at a mid-latitude site (Rattlesnake Mountain Observatory near Richland, Washington) obtained with an automated suntracking photometer (Michalsky et al. 1990). The time series of residual aerosol optical depth, obtained by subtracting a mean seasonal variation from the total aerosol optical depth (Michalsky et al. 1990), was extended with another year of data, as shown in Figure 1. The effects of the two major volcanic events, El Chichon and Mt. Pinatubo, are clearly seen. It is interesting to note that the decay of the volcanic perturbations to the stratosphere by El Chichon and Mt. Pinatubo is not monotonic in time, but shows pronounced seasonal oscillations, with secondary maxima in

aerosol optical depth occurring in the winter months. Moreover, the wavelength dependence of the residual aerosol optical depth appears to be quantitatively different for Mt. Pinatubo than the other volcanic events. The QLN now has collected data for 3 years. Although it is still premature to estimate a mean seasonal tropospheric signal from the data, it is now possible to compare and contrast the optical depth results derived from the QLN direct-beam measurements with those from the Rattlesnake Mountain site. Before presenting these results, however, it is useful to further discuss the analytical procedures.

Referring to Equation (1) and the discussion about the automated objective Langley algorithm, we have noticed in the analysis of data from the QLN sites that the I_0 s, after accounting for changes in sun-earth distance, are not reproducible from day to day to high precision. They are, however, consistent enough that averaging yields a robust estimate of the true I_0 , as confirmed by comparing the ad I_0 just after field deployment with standard lamp calibrations of the instrument just before field deployment. Because of soiling, filter drifts, and instrument repairs resulting in adjustments to the filter/detector head, the I_0 s can and do change, as illustrated in Figure 2. It is also our experience that the I_0 s either do not change within the accuracy of their variations, or the drift is linear in time and can be so approximated. Thus, using a median I_0 or an I_0 that varies linearly in time for each of the filter/detectors along with Equation (1) allows a calculation of total optical depth as a function of time.

The time-series of optical depth formed in this manner may be influenced by cloud effects. To eliminate time periods where cloudiness, including sub-visual cirrus, is a significant obscuration factor, an additional

RMO Aerosol Minus Background at Five Wavelengths

FIGURE 1. Residual Aerosol Optical Depth at Several Wavelengths Derived from Direct Solar Beam Measurements at Rattlesnake Mountain Observatory Since 1979 Showing the Effects of Volcanic Perturbations

I_0 from Langley Regression and Linear Fits Used (ASRC-500nm)

FIGURE 2. Variability and Linear Trends in I_0 Caused by Atmospheric Variability and by Detector Adjustment, Filter Drift, and/or Soiling

analysis procedure was implemented. In this procedure, 30-minute time periods are examined to look for cloud free periods where aerosol may change, but even thin-cloud passages are excluded by rejecting any point with a deviation from a linear drift with time (over the time interval) that exceeds 0.01 optical depth unit. If every point meets this strict criterion, an optical depth for the 30-minute time period is computed, and the next 30-minute interval is considered. If any outliers exceed this criterion, the time increment is advanced 5 minutes, and a new 30-minute period is examined. This procedure allows the aerosol optical depth to change slowly with time. Finally, daily averages are calculated from all 30-minute data intervals for a particular day. This latter step is important when analyzing the data for seasonal and annual changes, because it minimizes the extra weighting that otherwise would be given to the clearest days. Aerosol optical depth is obtained from the total optical depth by subtracting the Rayleigh scattering optical depth for each wavelength corrected for pressure and the resulting from ozone absorption in the Chappuis bands near 600 nm.

Figures 3-6 show plots of daily-ad aerosol optical depth at 500 nm from four QLN sites and cover a period of about 2.5 years. The solid line in these plots is a smoothed curve generated by a locally weighted, robust regression (lowess) function (Cleveland 1979). The number of points included in the estimate is chosen by the analyst. In this case, it includes all points within about a 3-month window. The lowess smoother gives less weight to points in time that are farther from the point for which the estimate is being made, as well as to points with optical depth values that are distant from the point in question even if a point is near in time. This prevents, in principle, extremely high or low optical depth points that are short lived from exerting much influence on the estimate. However, some artifacts can arise, especially at the end of a time-series, if the endpoint values tend to be at some distance from the

median. This is illustrated in Figures 3 and 5, where the extreme jump in the lowess curves at the end of the data period is an artifact of the lowess procedure and the high optical depths in the summer. The lowess curve should be ignored in this case.

From the plots, an overall decrease is seen each succeeding year at three of the sites, namely SUNY-Albany (Figure 3), University of Maine (Figure 4), and Illinois State Water Survey (Figure 6). This decrease is primarily a result of the decay of the stratospheric aerosol cloud from the Mt. Pinatubo eruption of June 1991. The effect of Mt. Pinatubo effectively masks the seasonal aerosol behavior for the Albany and Maine sites. Typically, northern mid-latitude sites exhibit a seasonal pattern with highest aerosol optical depth values in late-spring/early-summer and lowest values in winter. The volcanically imposed pattern is just the opposite, with highest optical depths in winter and lowest in fall. The volcanic seasonal pattern is also apparent in Figure 1 for the El Chichon and Mt. Pinatubo aerosol clouds observed over Rattlesnake Mountain. The Albany and Maine sites are relatively clean sites for locations east of the Mississippi River.

Results from the Bluefield State College site in southern West Virginia (Figure 5) are distinguishable from the Albany and Maine sites in the sense that no overall decrease is seen in successive years, and the summers tend to be very hazy with maximum aerosol optical depths. The Illinois State Water Survey site (Figure 6) near Bondville, Illinois, appears to show behavior intermediate to the Albany and Maine sites on one hand and the West Virginia site on the other, with a seasonal signal that reflects both the Mt. Pinatubo aerosol cloud and hazy summers. The remarkable aspect of the Illinois time-series is the obvious gap during summer 1993. This gap was the result of a combination of a severe storm event with lightning, typical of this site in the summer months, and delays in getting spare parts to the site to repair the damage, thus keeping the site out of commission for much of the summer.

asrc

FIGURE 3. Time-Series Aerosol Optical Depth at the Albany, New York, Quantitative Links Network Site Showing the Effects of Mt. Pinatubo Stratospheric Aerosol Decay

FIGURE 4. Time-Series Aerosol Optical Depth at the University of Maine (Howland, Maine) Quantitative Links Network Site Showing the Effects of Mt. Pinatubo Stratospheric Aerosol Decay

bsc

FIGURE 5. Time-Series Aerosol Optical Depth at the Bluefield State College Quantitative Links Network Site Showing the Effects of High Summer Haze

ISWS

FIGURE 6. Time-Series Aerosol Optical Depth at the Illinois State Water Survey (Bondville, Illinois) Quantitative Links Network Site Showing the Effects of Mt. Pinatubo Stratospheric Aerosol Decay and Summer Haze

Although the overall trend in decreasing optical depth between 1992 and 1994 is apparent, it is not possible to estimate with any certainty any changes that occurred during the middle of 1993.

The two papers on the MFRSR and the automated Langley analysis algorithm prepared in 1993 were published (Harrison and Michalsky 1994; Harrison et al. 1994). A third paper discussing the effects of Mt. Pinatubo aerosol on solar concentrator performance was also published (Michalsky et al. 1994a). Three papers dealing with the cosine response of radiometric instruments, retrieval of water vapor and ozone from MFRSR observations, and spectral corrections to solar irradiance measurements have been submitted for publication. Four papers were presented at conferences this year. Two papers on aerosol optical depth measurements at mid-latitude sites were presented at the American Meteorological Society (AMS) annual meeting at Nashville, Tennessee, January 1994, and the Air and Waste Management Association Specialty Conference at Snowbird, Utah, September 1994 (Laulainen et al. 1994b; Michalsky et al. 1994b), respectively. A paper on water vapor retrieval was also presented at the AMS annual meeting (Michalsky et al. 1994c). The fourth paper on spectral corrections to solar irradiance measurements was presented at the American Solar Energy Society meeting in San Jose, California, June 1994 (Zhou and Michalsky 1994).

Future Work

The major effort in FY 1995 will focus on summarizing the results from the QLN through its final year of operation. Analysis of data with respect to seasonal aerosol variations at each site and the effects of the Mt. Pinatubo eruption will continue. Other significant activities include the following:

- reduction of data for clear and partly cloudy days using the automated data reduction technique developed in 1994
- application of algorithms to extract aerosol size distributions, water vapor, and ozone total column from the total and aerosol optical depth data
- application of procedures to detect cirrus clouds and their thicknesses; testing and application of reliable automated algorithms that rely on the fact that cirrus clouds are highly variable, transparent, and yield size distributions that are very different from aerosol size distributions
- investigation of optical depths for opaque cloud cover; detection of opaque clouds by nulling the direct beam component; accumulating statistics on their frequency and thicknesses as measured by the diffuse irradiance component
- submission of a paper on the effects of the Mt. Pinatubo eruption to the *Journal of Geophysical Research*
- presentation of papers on optical depth and direct-to-diffuse irradiance measurements obtained with the MFRSR at the QLN sites to be presented at the International Radiation Symposium in the summer of 1995 in Fairbanks, Alaska
- preparation of papers on aerosol optical depth measurement and diffuse to direct irradiance ratios for submission to the *Journal of Geophysical Research*.

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Carbon Dioxide Ocean Research

Principal Investigators: J. P. Downing, W. E. Asher, D. W. Denbo, E. D. Skyllingstad, L. S. Bingler, and B. G. DeRoos

The goals of the Carbon Dioxide (CO₂) Ocean Research project are to develop improved models of ocean processes for climate research and new methods for estimating the carbon fluxes in the surface layer of the ocean. The objectives for FY 1994 were to 1) complete analysis of data from air-sea gas-exchange experiments conducted in 1992 and 1993 in an outdoor wave tank; 2) make large eddy simulations of oceanic convection and surface layer mixing, using the Ocean Large Eddy Simulation Model (OLEM) developed in prior years; and 3) develop new technologies for measuring the physical and chemical state of the ocean. Major progress was made toward all these objectives. First, full-scale geophysical experiments were undertaken with OLEM. During this past fiscal year, OLEM was used to understand the effects of wind, heat flux, and organized motions on mixing of the surface layer. OLEM was also used to determine the importance of forcing conditions in modeling deep convection. Second, work was completed on a new multi-parameter expendable probe for monitoring the oceanic environment, and third, a second highly successful gas-exchange experiment in a large outdoor wave basin was completed.

FY 1994 Accomplishments

The following sections give details of the progress made on the above objectives in FY 1994.

Air-Sea Exchange of CO₂

The accuracy of estimates of global ocean uptake of CO₂ can be improved through better understanding of air/sea gas exchange at high wind speeds. The research performed in FY 1994 achieved two very important milestones in our development of a method to estimate the air/sea transport velocity of CO₂ from remote measurements of whitecap co. First, gas transfer data collected in experiments conducted in the whitecap simulation tanks have been used to develop a parameterization of the gas transfer velocity in terms of whitecap co, Schmidt number, and aqueous-phase solubility. This parameterization can be used to describe both gas invasion and evasion, which makes it easy to incorporate it into global carbon cycle models. The second major milestone was obtained by analysis of the data collected during the October 1993 wave basin

experiment (WABEX-93). Concurrent measurements of passive microwave brightness temperature and transfer velocity made during the experiment show there is a linear relation between the two. This is important because it demonstrates it is possible to extend the relation between transfer velocity and whitecap co to a remote-sensing technique. Research in FY 1995 will focus on applying the empirical parameterization of transfer velocity developed using the whitecap simulation tank data to gas exchange in the ocean.

Convection, Surface Processes, and Convection Parameterizations

This year we made major improvements to our ocean large-eddy model (OLEM). These include a new initialization method, improved solution accuracy, and more efficient calculation of statistics of model variables. The proper spinup of OLEM requires that small-amplitude random fluctuations exist in the initial model fields. The new initialization procedure creates these fluctuations by adding

small perturbations to the potential temperature and vertical velocity fields in the mixed layer.

Deep convection process studies conducted during FY 1994 have led to a better understanding of the relationship between forcing parameters and the onset time and strength of deep convection. We have shown that the onset time is a strong function of the total amount of heat removed from the ocean surface rather than the magnitude of the heat flux. Moreover, the strength of deep convection is directly related to the magnitude of the heat flux. It therefore appears that an exact history of cooling is not needed to force models of deep convection, and furthermore, that high-frequency forcing of ocean general circulation models could be unnecessary for predicting the correct timing of convection. On the other hand, changes in the mixed-layer density can strongly affect the timing of convection events. Sensitivity experiments completed this year provide an empirical basis for understanding how these and other factors affect the convection process. The empirical relationships developed from these experiments have improved our understanding of the ocean's response to changes in forcing and environmental conditions and provide a basis for improving parameterizations used in climate models.

An accurate estimate of sea-surface temperature (SST) is critical for determining the climatological effects of air-sea heat and moisture exchange. This has been shown by coupled GCM studies in which the long-term stability of the oceanic thermohaline circulation is strongly linked to the specification of the surface boundaries.

Work performed in FY 1994 as part of the Surface Mixed Layer project centered on publishing results from two numerical experiments. These experiments demonstrate the importance of surface waves and subsequent Langmuir circulations on defining the turbulence structure of the mixed layer and the rate at which the mixed layer deepens. Mixed layer depth and structure are critical in determining the sea-surface

temperature, which is a primary variable in coupling the atmosphere and ocean heat budgets. We found that wave-current interaction caused as much as a factor of two increase in the growth rate of the mixed layer. A simplified analysis of the surface wave forcing showed that straightforward changes could be made to existing one-dimensional mixed-layer models to account for surface wave effects.

CO₂ Survey Support and Technology Development

The Battelle/Marine Sciences Laboratory (MSL) provided substantial support for the DOE Global CO₂ Survey in FY 1994. MSL scientists collaborated with the Instituto de Investigaciones Mariñas, Vigo, Spain, to make inorganic carbon measurements along World Ocean Circulation Experiment (WOCE) line A17 in the Atlantic Ocean. One hundred and forty five of 235 stations were sampled between January 4 and March 29, 1994, along a 50°W longitude, from 51°S to 6°N latitude. More than 3200 seawater samples were analyzed in 74 days, at a rate of 43 samples per day. We also conducted a detailed sampling along shore-normal sections along the east coast of South America to characterize carbon distributions caused by circulation at western ocean boundaries.

Laboratory studies on the stability of critical reagents used in the coulometric carbon analysis method, initiated in 1993, were completed this year. The studies demonstrated that as much as three times more carbon can be titrated by a coulometer cell than previously thought possible. Based on these findings, we routinely titrated 40 to 90 mg of carbon with each cell during the A17 cruise without compromising data quality. Therefore, instead of analyzing 44 samples per day using one cell, it was possible to analyze 63 samples per day, an increase of equivalent to half of a 5000-meter profile.

Technology development this year focused on sensor packages for obtaining hydrographic,

water chemistry, particle and current data inexpensively. In addition, long-term stability tests were completed on five solid-state pressure transducers in the high-pressure test facility at MSL. The test results indicate that solid-state pressure transducers are applicable to long-term autonomous monitoring at deep-ocean pressures. A U.S. patent application for ceramic pressure housings developed for this project was allowed and the patent will issue in early 1995. A new suite of sensors and miniature data logger were integrated in an autonomous system for underwater environmental monitoring. The system includes a sodium-iodide detector and multichannel analyzer for gamma radiation spectroscopy, flux-gate compass and tilt sensor for current velocity measurements, as well as particle, ion-selective electrode, pressure, temperature, and conductivity sensors.

Plans for FY 1995

Laboratory and field experiments to further develop the capability to predict exchange velocities for CO₂ from whitecap coverage through remote measurements will continue in FY 1995. Substantial effort will be directed toward analyzing and interpreting the results

from previous laboratory and field studies and preparing for an open-ocean experiment scheduled for winter 1996. The latter experiment will be conducted on Georges Bank, Massachusetts, in collaboration with the National Oceanic and Atmospheric Administration.

We plan to validate the wave-current parameterization used in OLEM by directly measuring both the wave velocity field and the circulations forced by the surface waves at a coastal site in FY 1996. This field study will provide the first extensive data set of velocity fields for understanding the formation of Langmuir circulations by wind and wave interactions. It will also provide essential data for establishing basic turbulent transport relationships for a wind- and wave-driven mixed layer.

Our plans for supporting the Global CO₂ Survey in FY 1995 include making carbon measurements along WOCE line A13 in the Atlantic in January 1995. Data from this area will provide continuity in the south Atlantic CO₂ data set. Plans for the Indian Ocean include carbon measurements along WOCE line I1 in September 1995 and I10 in November 1995.

Improved Parameterization for Deep Convection Processes in Ocean General Circulation Models

Principal Investigator: T. Paluszkievicz

Other Investigators: L. F. Hibler, R. Romea, E. D. Skyllingstad, D. W. Denbo

A one-dimensional penetrative plume model was constructed to parameterize the process of deep convection in ocean general circulation models (OGCMs). The parameterization was incorporated into the Parallel Ocean Climate Model (POCM) (Semtner and Chervin 1988), and the implementation and efficiency of the scheme within the POCM were tested. The effect of the parameterization on simulations of deep convection was evaluated in a regional domain, the Nordic Seas. The initial analysis of this test showed that the parameterization improved the degree of penetrative mixing under the preconditioned region. Sensitivity tests were performed to determine the optimum parameter ranges for scalable parameters such as the plume radius and threshold of instability. We are completing large domain (Atlantic basin and global-scale) simulations in collaboration with the Computational Hardware, Advanced Mathematics, and Model Physics Program (CHAMMP) science team members at the Naval Post Graduate School and at Los Alamos National Laboratory. This was the final year of the original project; the upcoming project will address extending the deep convection parameterization to be consistent with surface mixed-layer parameterizations.

FY 1994 Accomplishments

We achieved the following goals and objectives over the past year:

- incorporated the one-dimensional vertical mixing model to parameterize deep convection into the three-dimensional OGCM
- tested the implementation and efficiency of the parameterization in the OGCM
- refined the parameterization to improve efficiency within the OGCM
- investigated the sensitivity of the simulation to scalable parameters
- evaluated the OGCM simulations using the new parameterization.

Testing the Deep Convection Parameterization

We completed development and testing of a penetrative plume model Ocean Parameterized Plume Scheme (OPPS) and implemented the parameterization in the OGCM. The purpose of this parameterization is to improve OGCM simulations by including the physics of deep penetrative convection (thermobaric convection) and deep-water formation, without adding the complexity of a full large-eddy simulation (LES). To accomplish this, the parameterization scheme takes the temperature and salinity profiles of OGCM grid boxes and simulates the subgrid-scale effects of convection using a one-dimensional parcel model. The one-dimensional model moves water parcels from the surface layer down to their level of neutral buoyancy, simulating the effect of convective

plumes. While in transit, the plumes exchange water with the surrounding environment; however, the bulk of the plume water mass is deposited at the level of neutral buoyancy. Weak upwelling around the plumes is included to maintain an overall mass balance. The process continues until the negative buoyant energy of the one-dimensional vertical column is minimized. The parameterized plume entrainment rate, which plays a central role in the model physics, is calculated using modified equations based on Turner's (1973) entrainment hypothesis. This scheme differs from the convective adjustment techniques currently used in OGCMs because the parcels penetrate downward with the appropriate degree of mixing with the environment, until they reach their level of neutral stability.

POCM (Semtner and Chervin 1988) was configured for the Nordic Seas, and the process of preconditioning was simulated to develop a suitable testbed for evaluating the new deep-convection parameterization. The parameterization was incorporated into POCM, and the modified model was tested in the Nordic Seas test basin. The new convective parameterization replaced the standard convective adjustment algorithm. The use of the full equation of state, implemented through the look-up-table approach, was evaluated against the nonlinear approximation that is generally used. The use of the full equation of state improved the calculation of density at the very low temperatures in the Nordic Seas. The new convective parameterization was tested by evaluating the response to various levels of latent and sensible heat flux and to a range of levels of wind forcing.

The model domain for the simulations extended from 65°N to 81°N and 8°W to 8°E . The horizontal resolution was varied for different cases; simulations were run using $1/8^{\circ}$, $1/4^{\circ}$, $1/2^{\circ}$, and 1° resolution. All the simulations used flat topography with a depth of 2750 m and 16 vertical levels that correspond with those used by Semtner and Chervin (1988). The model was initialized with a climatological profile from the area. We also ran simulations

in the Gulf of Lyons for comparison. Ultimately, different scenarios of cooling and wind stress were evaluated to determine the optimum conditions for generating a preconditioned gyre. By using a combination of heat flux and wind forcing, the vertical stability of the water column was reduced, and the characteristic doming of the preconditioned gyre was generated. The wind forcing had the strength and characteristics of the strong, low-pressure systems that have been found in the Greenland Sea, with a maximum of 0.5 dynes (Legutke 1991). The cooling was a constant -200 W m^{-2} . These simulations revealed that the scale of the preconditioned gyre and the preconditioning response time varied, as expected, with the Rossby radius. As a consequence, the simulation of preconditioning is sensitive to the resolution used in the model. The behavior of the gyre-scale circulation and its response to various wind and heat flux conditions is in agreement with the theoretical model of Romea (1976). Cooling and a cyclonic circulation, together, are the essential ingredients for preconditioning. Neither cooling nor a cyclonic circulation alone resulted in the elevation of the pycnocline that is necessary to weaken the vertical stability and facilitate deep convective events. The results from these preliminary simulations were used to select a scenario for testing the new convective adjustment parameterization. An example of the circulation resulting from the preconditioning scenario is shown in Figure 1.

We ran POCM, with OPPS incorporated, in the Nordic Seas test basin and compared it with a "twin" POCM experiment that uses the standard convective adjustment algorithm. The test runs used $1/4^{\circ}$ and $1/2^{\circ}$ resolution in the horizontal and ran for 100 days. The tests used the same model configuration, vertical resolution, domain, and flat bottom. The temperature and salinity were initialized from a profile from Rudels et al. (1989). A cyclonic wind stress with a maximum of 0.5 dynes, a sensible heat flux of -100 W m^{-2} , and a latent heat flux

of 30 W m^{-2} , were used to generate a preconditioned gyre and to stimulate convection.

The test basin was subjected to wind forcing for 50 days to generate a cyclonic circulation (Figure 1). Following the 50 days of wind stress, the cooling and latent heat flux were initiated. During the next 50 days, the doming of the isopycnals and isotherms evolved. In the simulation using OPPS (the new convective parameterization) the convective activity is concentrated in the center of the doming. In contrast, in the simulation using the standard convective algorithm, the convective activity is found along the edges of the gyre (high shear regions) and along the thermocline. Convective activity was measured by using a counter that is triggered when the code performs a convective adjustment. At day 82.5, a snapshot from each simulation shows that doming is occurring in the center of gyre and that in the case using OPPS, there is significant mixing through the water column. In the case with the standard convective adjustment, doming is not well defined, and the mixing is taking place along the thermocline. At day 85, the doming breaks the surface, and the thermocline begins to erode, whereas in the standard convective adjustment case, mixing is still confined to the thermocline region (Figure 2). A possible explanation for the evolution of these fields (temperature, salinity, and density) is that a spurious vertical velocity from the high shear regions near the boundary triggers a disturbance along the thermocline that, in turn, requires convective adjustment. This pattern of thermocline disturbance continues so that all the effective mixing occurs in this region. The simulation with OPPS differs because it accommodates partial mixing through the vertical levels, governed by the available buoyant energy budget, using entrainment physics to govern the degree of mixing. Consequently, the stability is quickly found by creating a mixed, stable water parcel.

In the standard convective adjustment case, two vertically adjacent particles are mixed to

remove the instability. The top five to six levels have very small changes in the temperature and salinity variables; therefore, the mixing between the adjacent levels removes small amounts of the instability, and the evolution of the cooled feature proceeds very slowly. These results indicate that the OPPS convection scheme leads to more penetration and that there is less horizontal homogenization of the intermediate levels than with the standard adjustment scheme (Figure 2). The top panel of Figure 2 shows the convective cells forming in a simulation from POCM using OPPS for a convective adjustment scheme. The lower panel is from POCM using the standard convective adjustment scheme; notice that in the bottom panel, the convective adjustment occurs throughout the domain rather than in the domed, preconditioned gyre and is not penetrative. In the horizontal plane, an X-Y slice at 300 m shows that the mixed area in the center of the dome has irregular edges for the simulation using OPPS. This reflects the influence of the partial mixing, as opposed to the overall homogenization that the standard convection algorithm generates (Figure 3a and b).

In addition to analyzing the modified circulation and water mass structures, we compared efficiency data from the simulations of POCM with OPPS incorporated. To work in global, climate-scale simulations, we modified the parameterization to be more computationally efficient. Testing of the new, more efficient OPPS is underway. In collaboration with investigators at the Naval Post Graduate School and National Center for Atmospheric Research, we are designing simulations of POCM with OPPS incorporated for a global domain. These simulations will be run over longer time scales, and at coarse resolution, to determine the sensitivity of the thermohaline circulation to this change in parameterization. Tracers will be used to help determine whether the deep water produced through deep convection is produced on the correct time scale.

50 days 12.0 hours
300 m Depth (Using Standard Adjustment Scheme)

FIGURE 1: Horizontal Section of Velocity and Temperature at 300 m after 50 days of a Cyclonic Wind Stress. A potential temperature contour, -1.34°C , shows the beginning of the doming of the temperature and density fields.

FIGURE 2: The Potential Temperature versus Depth from a Section at 75°N in an Idealized Nordic Seas Domain. POCM was spun-up for 50 days using a cyclonic wind stress, then cooling was initiated.

FIGURE 3a: Horizontal Section of Velocity and Temperature at 300 m after 95 Days of a Cyclonic Wind Stress and Cooling Starting on Day 50. Potential temperature contours show the extent of the mixing within the gyre.

FIGURE 3b: Horizontal Section of Velocity and Temperature at 300 m after 95 Days of a Cyclonic Wind Stress and Cooling Starting on Day 50. Potential temperature contours show the extent of the mixing within the gyre.

Sensitivity Analysis for Selecting Scalable Variables in OPPS

Within OPPS, three scalable variables must be determined. We explored the theoretical, observational, and numerical evidence for choosing the ranges of these variables. The three variables of interest are the entrainment constant, the plumelet radius, and the initial vertical velocity of a parcel displaced in a plume. The entrainment constant cannot be obtained theoretically and must be taken from laboratory and field experiments. A survey of laboratory experiments showed that a reasonable value for this constant is 0.10. The estimates for the initial plume radius were obtained from analysis of direct observations in the ocean, instability theory for rotating and nonrotating convection, and analysis of the results of the high resolution LES model experiments of Denbo and Skillingstad (1994). We performed a survey of observations and an analysis of LES model results to obtain plume radius statistics from which to develop a relationship and range of values. The results of this analysis and more extensive theoretical work by Denbo and Skillingstad (1994) showed that individual plume radii for rotating convection are 20% smaller, and that instability theory cannot strictly define the plume radius. We are conducting a series of statistical evaluations to evaluate the model's sensitivity to using a range of plume radii in contrast to using a single fixed radius. We are finishing a similar analysis of the initial plume vertical velocity.

Other Activities

During the course of evaluating the "improvement" of ocean circulation simulations that used the OPPS parameterization, it became evident that no well-known objective solution (simulation) existed with which to compare to determine the correctness of the simulation.

This is a long-standing problem of ocean model development. To begin to address this problem, we organized and ran a workshop to define ocean model test problems and to define reference solutions. The U.S. Department of Energy's (DOE) High Performance Computing Center (HPCC) Program provided support for this workshop as part of the HPCC's climate modeling grand challenge collaboration with the DOE's CHAMMP program. The Ocean Model Test Problems workshop was held in Santa Fe, New Mexico, September 17-18, 1994, and was attended by 11 scientists from U.S. and international academic institutions and the DOE national laboratories. The motivation for the workshop and for defining ocean model test problems comes from the expanding variety of new and innovative methods being used to revolutionize ocean models; these innovations arise from the inevitable advances in the field, the sharing of techniques between atmospheric sciences and aeronautical engineering, and the availability of massively parallel computers. The first goal of the meeting was to define a set of ocean model test problems to use to evaluate numerical methods used in ocean circulation models proposed for climate modeling and to identify the potential tradeoffs that must be made in numerical modeling. The second goal was to choose a model and develop a plan to calculate the reference solutions to the test problems.

The workshop participants defined a suite of six principal test problems and two challenge problems. Individuals from the workshop are actively writing detailed descriptions of the six principal problems and the reference solutions. The challenge problems are active research areas that require further investigation and discussion. The workshop concluded with a plan to complete the detailed descriptions of the

test problems and reference solutions and to compose a news article describing the workshop and results.

Plans for FY 1995

In the coming year, we will complete the ongoing analysis of the sensitivity to selected variables in the parameterization. In addition, we will complete the global-scale simulations and analyze the effectiveness of the deep convection parameterizations. Under the next phase of this CHAMMP project, we will determine how best to combine the convective parameterization with a wind-mixed layer parameterization. We will further investigate modifications to the parameterization that could be needed once an ice model is coupled to the OGCMs in use by other CHAMMP investigators.

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