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Pacific Northwest Laboratory Annual Report for 1992 to the DOE Office of Energy Research

Part 3 Atmospheric and Climate Research

Staff Members of Pacific Northwest
Laboratory

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MASTER

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PREFACE

This 1992 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 1992. This year the report consists of four parts, each in a separate volume.

The four 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 in the Office of Energy Research. In some instances, the volumes report on research funded by other DOE components or by other governmental entities under interagency agreements. 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 1992 Annual Report are:

Part 1: Biomedical Sciences
Program Manager: J. F. Park — J. F. Park, Report Coordinator; S. A. Kreml, Editor

Part 2: Environmental Sciences
Program Manager: R. E. Wildung — L. K. Grove, Editor

Part 3: Atmospheric Sciences
Program Manager: W. R. Barchet — R. E. Schrempf, Editor

Part 4: Physical Sciences
Program Manager: L. H. Toburen — L. H. Toburen, Report Coordinator; W. C. Cosby, 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 four parts, and to Ray Baalman, editor in chief, who directed the total effort.

T. S. Tenforde
Health and Environmental Research Program

Previous reports in this series:

Annual Report for

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
1972	BNWL-1750, Vol. 1, Pt. 1-2; BNWL-1751, Vol. 2, Pt. 1-2
1973	BNWL-1850, Pt. 1-4
1974	BNWL-1950, Pt. 1-4
1975	BNWL-2000, Pt. 1-4
1976	BNWL-2100, Pt. 1-5
1977	PNL-2500, Pt. 1-5
1978	PNL-2850, Pt. 1-5
1979	PNL-3300, Pt. 1-5
1980	PNL-3700, Pt. 1-5
1981	PNL-4100, Pt. 1-5
1982	PNL-4600, Pt. 1-5
1983	PNL-5000, Pt. 1-5
1984	PNL-5500, Pt. 1-5
1985	PNL-5750, Pt. 1-5
1986	PNL-6100, Pt. 1-5
1987	PNL-6500, Pt. 1-5
1988	PNL-6800, Pt. 1-5
1989	PNL-7200, Pt. 1-5
1990	PNL-7600, Pt. 1-5
1991	PNL-8000, Pt. 1-5

FOREWORD

Within the U.S. Department of Energy's (DOE's) Office of Health and Environmental Research (OHER), the atmospheric sciences and carbon dioxide research programs are part of the Environmental Sciences Division (ESD). One of the central missions of the division is to provide the 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 definition and implementation of a sound national energy strategy. 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 ESD, the Atmospheric Chemistry Program (ACP) continues DOE's long-term commitment to study the continental and oceanic fates of energy-related air pollutants. Research through direct measurement, numerical modeling, and laboratory studies in the ACP emphasizes the long-range transport, chemical transformation, and removal of emitted pollutants, oxidant species, nitrogen-reservoir species, and aerosols. The Atmospheric Studies in Complex Terrain (ASCOT) program continues to apply basic research on density-driven circulations and on turbulent mixing and dispersion in the atmospheric boundary layer to the micro- to mesoscale meteorological processes that affect air-surface exchange and to emergency preparedness at DOE and other facilities.

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 1992 in each of these areas. A divider page summarizes the goals of each area and lists the projects that support research activities.

CONTENTS

Atmospheric
Research

ATMOSPHERIC RESEARCH

Atmospheric research at the Pacific Northwest Laboratory (PNL) focuses primarily on two areas: the fate of energy-related pollutant emissions as they are transported and processed in the atmosphere, and the flow of air in complex terrain. Analyses of the regional-scale transport of emissions address the physical and chemical processes that occur in clear and cloudy air; the formation of aerosols; the interaction of gases, particles, and clouds; and the simulation of these features on regional scales. Analyses of airflow in complex terrain investigate what roles energy exchange, terrain configuration, and scale interactions for coupled flows (e.g., slope, valley, and gradient) play in developing and destroying boundary-layer circulations and in dispersing contaminants. Research activities include field experiments, data analysis, and modeling simulations.

In FY 1992, PNL scientists participated in field experiments that were part of the U.S. Department of Energy's (DOE's) Atmospheric Chemistry Program (ACP) and the Atmospheric Studies in Complex Terrain (ASCOT) program. The ACP field study, based in Halifax, Nova Scotia, investigated gas-phase chemistry and aerosol dynamics in the aged pollutant plume from eastern North America over the remote western North Atlantic Ocean. This study is part of DOE's contribution to the international and multi-agency North Atlantic Regional Experiment. Field studies supporting the ASCOT program included measurements of boundary layer vertical structure near DOE's Rocky Flats Plant and an investigation of heat, momentum, and moisture fluxes over an arid surface. PNL was also the host for a major field study on the source area for near-surface fluxes of trace gases.

Numerical computer models are used to help analyze the results of measurement programs and to carry out numerical experiments that extend the range of conditions being studied. A box model using two chemical mechanisms was developed to simulate atmospheric chemistry over the western North Atlantic Ocean. Mesoscale boundary layer models were applied to the Tennessee Valley and to the Hanford area to investigate wind and airflow patterns. These investigations are systematically increasing the reliability of theoretical descriptions and models. Such models hold the promise of translating descriptive and forecasting capabilities to the great number of locations where boundary-layer flow and contaminant dispersion and removal are significantly influenced by terrain features, surface energy exchange, and regional characteristics of meteorology and atmospheric chemistry.

Interpretive analysis continued on ACP data obtained in the Persian Gulf. The coupling of observations with conceptual and numerical models has given insight into the origins and consequences of wind fields, pollutant dispersion, and flow patterns for the Grand Canyon, Tennessee Valley, Brush Creek Valley (Colorado), and Roanoke Basin (Virginia) areas.

The following articles present summaries of the progress in FY 1992 under these research tasks:

- **The 1992 Atmospheric Chemistry Program**
- **Research Aircraft Operations**
- **ASCOT Program Management**
- **Coupling/Decoupling of Synoptic and Valley Circulations**
- **Atmospheric Diffusion in Complex Terrain**
- **Interactions Between Surface Exchange Processes and Atmospheric Circulations**
- **Direct Simulations of Atmospheric Turbulence.**

Atmospheric Research

The 1992 Atmospheric Chemistry Program

C. M. Berkowitz, K. M. Busness, D. S. Covert,[a] R. C. Easter, M. Terry Dana, E. G. Chapman, J. M. Hales,[b] D. V. Kenny,[c] P. McMurry,[d] R. D. Saylor, W. J. Shaw, W.G.N. Slinn, S. B. Smyth, C. W. Spicer,[c] L. K. Peters,[e], J. M. Thorp, and M. L. Wesely[f]

The Atmospheric Chemistry Program (ACP) is one of the U.S. Department of Energy's (DOE) multi-laboratory programs of research on atmospheric processes. The ACP succeeds the Processing of Emissions by Clouds and Precipitation (PRECP) project and extends the scope from source-receptor relationships in acidic deposition to global environmental effects of energy-related activities.

The primary objective of the ACP is to provide information on atmospheric chemistry for the National Energy Strategy. The FY 1991 program included a major field campaign to the Persian Gulf to sample the fire plumes associated with the destruction of well heads in Kuwait. The results, related to climate and health effects of the plume, are included in an article to be published in the *Journal of Geophysical Research*. A doctoral dissertation and two additional articles for the *Journal of Geophysical Research*, describing the results of this field campaign, are also in preparation.

The field study in FY 1992 focused on collecting data that will allow the testing of specific hypotheses concerning energy-related pollutants and their global environmental effects. The primary tool for this field study was the Pacific Northwest Laboratory (PNL) Gulfstream I (G-1) aircraft (Figure 1). The G-1 aircraft was equipped with several unique instruments allowing sensitive detection of trace gas species, aerosol particles, and turbulence. One of the purposes of the FY 1992 field study was to test this new instrumentation (see "Research Aircraft Operations" in this volume) while evaluating the pollutant mix over the western North Atlantic.

The FY 1992 field study focused on aerosols, which is consistent with the increasing recognition of their importance for energy policies related to visibility, precipitation chemistry, and climate change. Through their roles in forming clouds and scattering solar radiation, aerosols have a major impact on the Earth's radiation budget. Also, heterogeneous chemical reactions on aerosol particles are suspected of being the prime cause of lower-stratospheric ozone loss in mid-latitudes (e.g., associated with volcanic eruptions and carbonyl sulfide oxidation [Covert et al. 1991]).

Of obvious fundamental importance is particle creation (or "nucleation"). Theoretical and laboratory results suggest that sulfate particle nucleation depends on preexisting particle concentration and size distribution, relative humidity, temperature, and the concentration of gaseous sulfuric acid. By analyzing shipboard observations, Professor Dave Covert at the University of Washington (Covert et al. 1991) found a correlation between moisture, temperature, and ultrafine particles (i.e., particles having a characteristic length scale of nanometers). Correlations between preexisting particles, moisture, temperature, and sulfuric acid have yet to be observed and were therefore sought in our 1992 field studies.

The search for these correlations appeared feasible in light of the predicted extreme sensitivity of particle nucleation rate to humidity and temperature. In the absence of other sources of particles, the particle number density is related to the nucleation rate. Consequently, localized regions of high ultrafine particle concentration, in conjunction with low concentration of larger particles and relatively high concentrations of gaseous sulfuric acid, would provide data in support of the nucleation theory.

In principle, all necessary quantities can be measured using the G-1 research aircraft. The new

(a) University of Washington, Seattle, Washington.
(b) EnvAir Corporation, Kennewick, Washington.
(c) Battelle Columbus Laboratories, Columbus, Ohio.
(d) University of Minnesota, Minneapolis, Minnesota.
(e) NORCUS/The University of Kentucky, Lexington, Kentucky.
(f) Argonne National Laboratory, Argonne, Illinois.

FIGURE 1. The PNL Gulfstream I Aircraft.

instrumentation, in conjunction with the existing capability to measure SO_2, O_3, NO_2, NO_x, CO, and standard meteorological parameters (temperature, relative humidity, and winds) formed the basis for planning the 1992 field campaign.

There were two major reasons for selecting the western North Atlantic as a study site. First, this region is a potential receptor region for anthropogenic chemicals transported from the United States. By using fast-response instruments with improved detection limits for evaluating air quality over a region with chemical mixes that are typically 1 to 3 days old, a better understanding of transport, transformation, and deposition processes could be obtained. The G-1 aircraft was stationed at Halifax, Nova Scotia, and generally flew south and west to near Boston, Massachusetts to sample chemical mixes having a range of ages (Figure 2).

The second reason for selecting the western North Atlantic was the possibility of combining scientific resources with those from other organizations participating in the North Atlantic Regional Experiment (NARE). NARE is a multinational investigation of (among other topics) the fate of continental emissions that are transported over the North Atlantic, which is also a key objective of DOE's ACP. A second objective shared by the ACP and NARE is to improve understanding of the chemical and physical origin and evolution of cloud condensation nuclei in oceanic atmospheres. Working with NARE also facilitates the exchange of ideas between DOE/ACP scientists and staff at other institutions. NARE will provide cooperation for future research in the region.

Project Goals/Objectives for FY 1992

During the past year, the objectives of the project were to

- provide information on atmospheric chemistry necessary to meet DOE policy and planning needs, as described in the National Energy Strategy
- complete the analysis of data collected in support of DOE's 1991 investigation of the Kuwait oil well fire plumes
- design and conduct a field program to test several advanced analytical tools having the capability to measure a variety of gases at

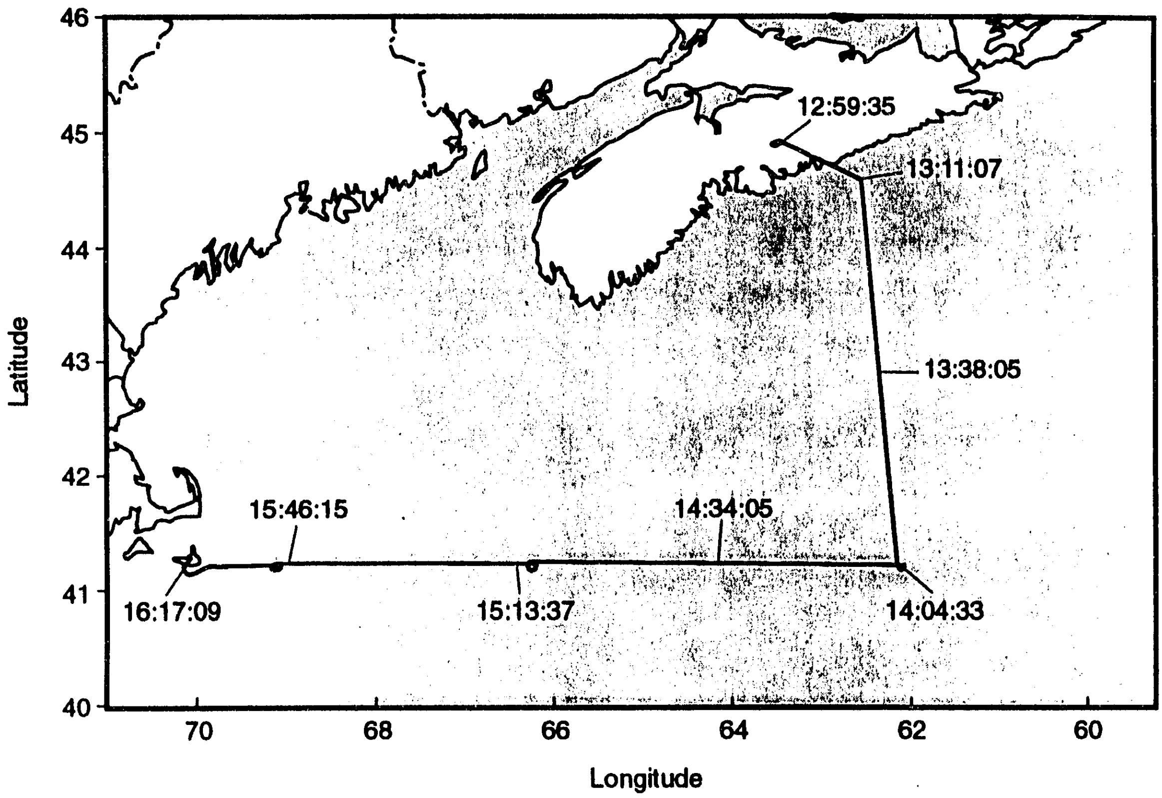

FIGURE 2. Study Area for the 1992 ACP Field Study (NARE '92), and a Flight Track for September 13, 1992. Numbers indicate time aircraft was at each location.

concentrations in the parts per trillion (ppt) range, and to measure particle size distributions down to the nanometer range

- use the information obtained from these instruments to examine the abundance and distribution of particles and selected gases over the western North Atlantic (Figure 2); this objective was to be met both through direct analysis of the data collected during the field campaign and by modeling studies to support this analysis
- gather information necessary to evaluate particle formation from the gas phase; this objective was also to be met through a combination of direct analysis of field data and modeling studies.

FY 1992 Accomplishments

Surveys and assessments of atmospheric chemistry literature relevant to energy-policy decisions have appeared regularly in the ACP's newsletter *Monthly Update*. A major effort in support of DOE planning was the preparation of a draft description of the ACP's plans for a project on lower-stratospheric and upper-tropospheric ozone concentration changes. This project will focus on 1) evaluating ozone and UV-B trends, 2) determining critical chemical and meteorological processes, and 3) applying these process results in global-scale predictive models. Emphasis will be on ozone changes in mid-latitudes and on testing predictive capabilities against field data measured in this ACP's Ozone Project.

As previously mentioned, the FY 1991 field program included a campaign to the Persian Gulf. Analysis of the data collected by the G-1 aircraft has focused on two issues: 1) the importance of gas-phase photochemistry in the plume as it traveled downwind, and 2) the evolution of the particle size distribution. Continuity equations for the ratio of reactive to nonreactive species are being used to evaluate the diffusion and transformation rates within the plume. The results are to be included in a doctoral dissertation being prepared at the Georgia Institute of Technology.

During preparation for the FY 1992 field studies, four advanced analytical tools were modified for use onboard the G-1 aircraft. One of these was the trace atmospheric gas analyzer (TAGA), a triple quadrupole mass spectrometer. A series of test flights near Columbus, Ohio, during January 1992 and further tests in August, just prior to going into the field with NARE '92, confirmed the operational status of the TAGA. During the second set of tests, the TAGA was also evaluated for sensitivity to altitude and detection limits for key species.

Calibration procedures were developed or adapted for the NARE target species. The most appropriate ionization modes and parent/daughter ion combinations for each target chemical were determined. Once the monitoring approach for a target chemical was optimized, calibration procedures were used to determine response factors and estimates of detection limits. The ten target chemicals could not all be monitored simultaneously because different ionization modes and reagent gases are required. The ten species monitored during NARE '92 thus fell into four groups, listed in Table 1.

A second state-of-the-art instrument installed onboard the G-1 aircraft was an ultrafine condensation nucleus counter (Thermal Systems Incorporated 3025 (TSI 3025), modified by Professor Dave Covert of the University of Washington). This ultrafine condensation nucleus counter (CNC) was installed in parallel with PNL's standard CNC (TSI 3020) in a configuration that allowed real-time monitoring of particles in the nominal size range from 3 to 10 nm. During a short exploratory flight over the Pacific Ocean in July 1992, measurements from this system showed several pockets of air that contained significant concentrations of ultrafine particles, surrounded by air that contained almost none. Although this test was not considered definitive, these observations of heterogeneous structure are consistent with aerosol nucleation theory. The TSI 3025 was subsequently modified to operate in a pulse height mode to provide size-resolved measurements for particles in the ultrafine range.

TABLE 1. The Ten Species Monitored by the TAGA During NARE '92.

Group A	Group B	Group C	Group D
HNO_3	HCOOH	NH_3	DMS
HONO	CH_3COOH		
H_2SO_4	Cl_2		
	SO_2		
	PAN		

A second aerosol measuring system, the scanning electrical mobility spectrometer (SEMS), supplied by Professor Peter McMurry of the University of Minnesota, permitted measurements of particles in the size range from 30 to 500 nm. This SEMS is a modified differential mobility analyzer that allows fast time-response monitoring of particles in this size range.

A final analytical tool added to the G-1 aircraft was a five-hole pressure port system for measuring atmospheric turbulence. When combined with the TAGA and inertial navigation system, this tool gives the potential of making the first airborne measurements of fluxes of trace chemical species using eddy correlation techniques. Funding for developing this capability was shared by the ACP and the Atmospheric Radiation Measuring Program (ARM).

Data to test the gust probe system was collected at the National Oceanic and Atmospheric Administration's Boulder (Colorado) Atmospheric Observatory tower. Fast-response sensors provided by Argonne National Laboratory measured fluxes of total gaseous sulfur at the 250-m level of the tower, while the G-1 aircraft system sampled SO_2 and turbulent fluxes during fly-bys. This cross-comparison provided data that should be useful in the analysis of the NARE '92 over-ocean flux measurements.

The timing for the NARE '92 field studies was based primarily on fog climatology and length of day. Climate statistics showed the occurrence of fog to be at a minimum between late August and early September. Flights were scheduled for mid-morning and early afternoon to avoid the relatively frequent occurrence of fog during early morning and late afternoon/early evening. Weather conditions grounded the aircraft only a few times during its deployment in Halifax.

Sampling strategies for the G-1 aircraft during NARE '92 were designed to maximize the horizontal distance of a given flight while still providing information on the vertical structure. This was accomplished by flying horizontal transects interspersed with vertical profiles. A typical flight plan was based on the predicted parcel trajectory provided by the Regional Forecasting Office of the Canadian Atmospheric Environment Service. Using these predicted trajectories, the G-1 aircraft was routed toward air that was expected to have come from the United States. The flight path usually alternated between low-level (150 m above sea level) and upper-level (1500 m above sea level) horizontal sampling, interspersed with spiral flight patterns between 90 and 2400 m. Approximately 80 hours of research flying during 20 missions were carried out with this strategy. Table 2 lists the missions and dates.

Preliminary results based on data that were reduced during the field program include the following:

- measurements of dimethylsulfide (DMS) with the TAGA, concurrent with gust probe turbulence measurements--these data could allow for the first-ever calculation of DMS flux; fluxes of SO_2 and formic acid are also being developed from the field data
- observed elevated plumes of ozone, NO_x, and aerosols in this semi-remote area (Figure 3); the mechanism for this long-range transport is not clear
- observed elevated plumes of ozone in this semi-remote area, with no associated NO_x or CO; the source for this ozone is unknown
- ultrafine (nanometer scale) aerosol number density measurements that showed an increase (by orders of magnitude) toward the top of the boundary layer under very clean air conditions (Figure 4).

A series of modeling studies was initiated in support of the NARE '92 field campaign. Two well-known gas-phase chemical mechanisms were coded into zero-dimensional, time-dependent box models. One of the mechanisms was designed for studies of background tropospheric chemistry in locations remote from significant anthropogenic influence. The other was designed for use in heavily polluted environments. The major difference between their treatment of NO_x, O_3, and other photochemically active trace species lies in their treatment of background CH_4/CO chemistry,

TABLE 2. Summary of NARE '92 Scientific Missions from Halifax, Nova Scotia.

Flight Number	Year-Month-Day	Flight Duration	Remarks
21	920914a	3h00m	Halifax to oil rigs S to 41N, 61W to Halifax
20	920913b	3h40m	Nantucket to Halifax
19	920913a	3h40m	Halifax to Nantucket
18	920911a	2h50m	Halifax to Sable Island to Halifax
17	920910b	2h30m	Halifax to Sable Island to Halifax
16	920910a	2h30m	Halifax to Hul (New Brunswick) to Halifax
15	920908b	2h00m	Sept Iles to Halifax
14	920908a	2h45m	Halifax to Sept Iles
13	920905a	3h10m	Halifax to Sable Island to Halifax
12	920903a	2h00m	Halifax and vicinity
11	920902b	2h50m	Nantucket to Halifax
10	920902a	2h50m	Halifax to Nantucket
9	920831a	4h50m	Halifax to Sable Island to Halifax
8	920830a	3h35m	Halifax to 41N, 61W to Halifax
7	920829a	1h55m	Halifax and vicinity
6	920826a	3h30m	Halifax to 41N, 61W to Halifax
5	920825a	1h00m	Halifax and vicinity
4	920824a	3h50m	Halifax to 41N, 61W to Halifax
3	920823b	1h55m	Nantucket to Halifax
2	920823a	4h15m	Halifax to Nantucket
1	920821a	2h50m	Nantucket to Halifax

Ozone

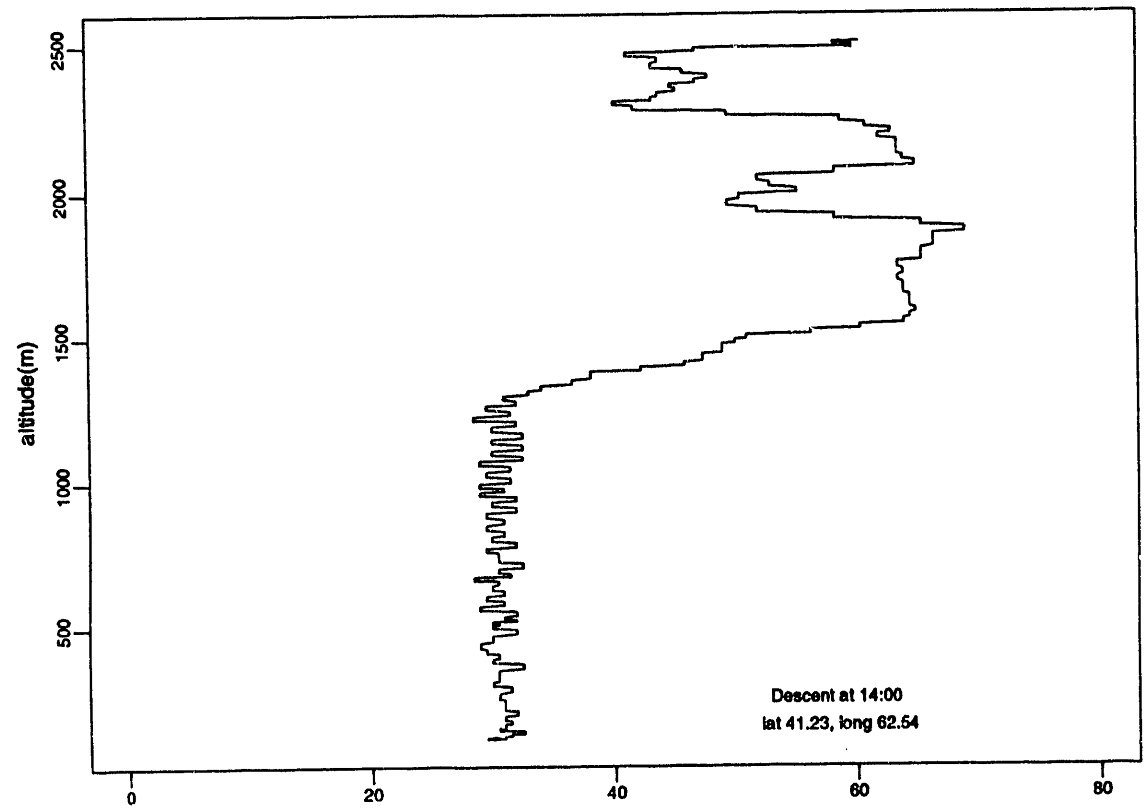

FIGURE 3. Typical Elevated Plumes Detected During NARE '92.

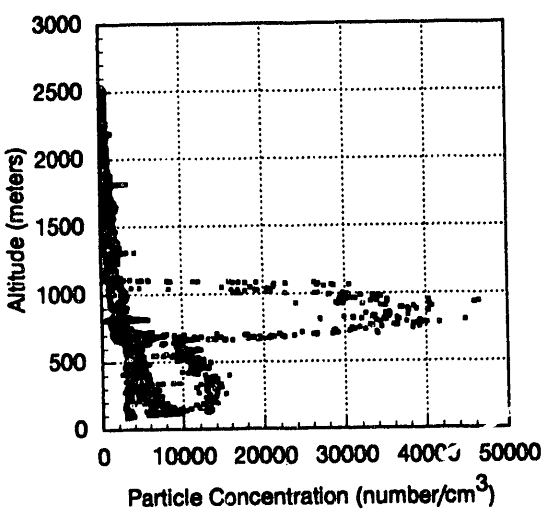

FIGURE 4. Elevated Ultrafine Aerosol Particle Number Density Near the Top of the Boundary Layer, Detected During NARE '92.

which is absent in the urban mechanism. A third mechanism is being designed that will be applicable in both clean and heavily polluted environments. These box models are intended to serve as preparation for the use of a regional-scale, comprehensive Eulerian model, as well as to provide information for the design of the NARE '93 field study (see below).

Plans for FY 1993 and Beyond

There are three general objectives for FY 1993. First, we plan to continue the reduction of data collected during the FY 1992 field study. Plans call for making these data, along with supporting documentation, available to the general atmospheric chemistry community. The second key objective for FY 1993 is the analysis of these data. The results of our analyses will be published in a series of journal articles.

Finally, based on analysis of the FY 1992 observations, we plan to design and execute a similar field study during FY 1993 in coordination with the National Oceanic and Atmospheric Administration (NOAA) and the Atmospheric Environment Service (AES) of Canada, which plan to operate research aircraft in the same region. Our involvement with these agencies under the NARE banner should greatly enhance measurement capabilities during NARE '93.

Reference

Covert, D. S., V. N. Kapustin, P. K. Quinn, and T. S. Bates. 1991. "New Particle Formation in the Marine Boundary Layer." *J. Geophys. Res.* 97(D18):20,581-20,589.

Research Aircraft Operations

K. M. Busness, R. V. Hannigan, S. D. Tomich, O. B. Abbey, and W. A. Garrity

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. The G-1 aircraft serves as an advanced airborne sampling platform, with the capacity to accommodate a wide variety of instrumentation in support of field programs dedicated to achieving the objectives of the DOE Atmospheric Chemistry Program (ACP).

FY 1992 Activities

In August and September 1992, the trace atmospheric gas analyzer (TAGA) 6000E[a] was successfully used for the first time in an airborne measurement mode during the pre-NARE (North Atlantic Regional Experiment) field program in the western North Atlantic. The TAGA is a laboratory-quality tandem triple quadrupole mass spectrometer that is highly sensitive and highly selective in measuring a wide range of organic and inorganic chemical species. A major operational advantage of the TAGA is its ability to function in an atmospheric pressure chemical ionization (APCI) mode, permitting rapid-response, real-time measurements in ambient atmospheric conditions.

(a) Sciex, Thornhill, Ontario, Canada.

This exciting application was the culmination of several years of work that began in late 1987 when the TAGA was first flown on PNL's DC-3 aircraft in a preliminary feasibility test (Busness 1991). The significance of this application was recognized immediately, but several technical challenges had to be met including modifications to the aircraft and TAGA to permit its installation and operation in PNL's G-1 aircraft (Berkowitz et al. 1992). The TAGA/G-1 merger was further delayed when the G-1 aircraft was deployed to the Mideast in 1991 to participate in a multiagency effort to characterize the smoke plume emanating from the Kuwait oil fires (Busness et al. 1992).

In its standard 'laboratory-bound' configuration, the TAGA is 100 in. long, 28 in. wide, 56 in. high, and weighs over 1200 pounds. The modified TAGA configuration consists of three main components, each small enough to be transported through the aircraft door and cabin passageway. In the aircraft, these three components are interlocked and mounted on a platform that was specially designed to provide safe structural stability and protection from aircraft vibration. Figure 1 shows the main TAGA components in their interlocked configuration. Inflight measurements of aircraft vibration characteristics were previously made during all phases of flight operation, and TAGA response to the vibration spectrum was tested in the laboratory to develop an appropriate physical mounting design. The physical mounting includes a large mounting plate that provides broad weight distribution, vertical supports for lateral stability, and vibration isolators to minimize in-flight vibration effects and shock during takeoff and landing.

In addition to the three main components of the TAGA, a roughing pump and large cryogenic pump are required to achieve the very high vacuum necessary for operation. The extensive power required to operate the cryogenic pump required a modification to the G-1 electrical power system in which an auxiliary generator was custom-mounted on the left engine accessory gearbox pad. The TAGA requires uninterrupted power because loss of vacuum for only a few minutes requires a 5-hour pumpdown of the instrument. Using only previously existing aircraft generators provided insufficient power to ensure safe operation of emergency aircraft systems during takeoff; it was therefore necessary to add the auxiliary generator to

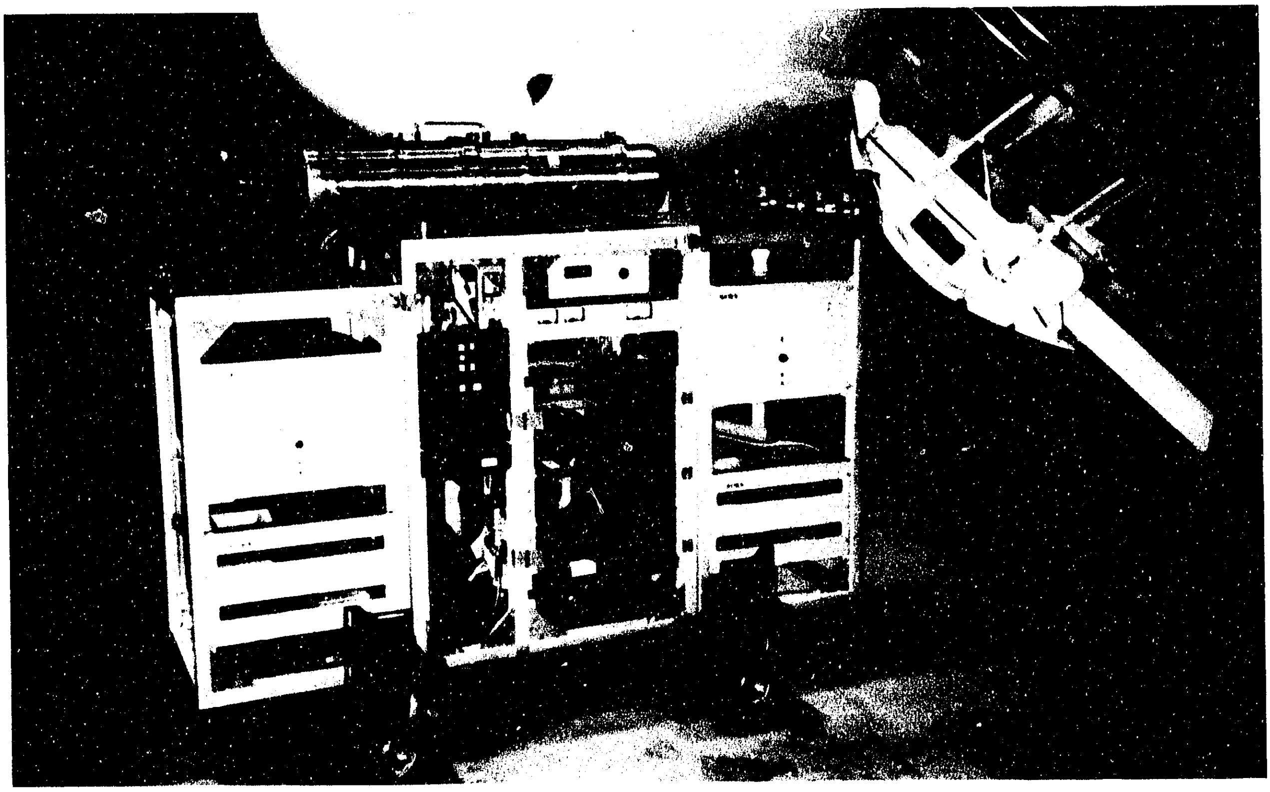

FIGURE 1. TAGA Main Components.

provide the power required by the cryogenic pump. The auxiliary generator provides an additional 300 amps of 28 VDC power, independent of other aircraft power systems. A series-parallel configuration of DC/AC inverters converts the 28 VDC to the required 220 VAC 60 Hz power. It was also necessary to develop provisions for switching between ground-based power and aircraft power without interrupting instrument operation.

In January 1992, after both the G-1 aircraft and TAGA were modified, the TAGA was installed and a demonstration flight to further test the total system was completed near Columbus, Ohio. During the successful test, several organic and inorganic acids and dimethyl sulfide were measured over horizontal transects and in vertical profiles (Kenny et al. 1992).

The TAGA response time for single-species monitoring is about 0.2 seconds (5 Hz). Because the G-1 aircraft is also equipped with a gust probe for detecting rapid fluctuations of vertical and horizontal winds, the TAGA's rapid response should enable flux measurements to be made using the eddy correlation technique for specific species. Normally, the TAGA is controlled and monitored by its own computer system, but it became apparent that it would be difficult to synchronize the multiple computers on the aircraft, and that a faster sampling rate would be necessary to capture data appropriate to flux calculations. Thus, a direct interface was developed between the TAGA and the aircraft data acquisition system, so that TAGA data could be acquired and recorded simultaneously with all other research parameters. The last step in the interface process was completed just prior to deploying the G-1 aircraft for the NARE '92 field study. Flux measurements for dimethyl sulfide and certain acids were conducted during the NARE '92 study (see "The 1992 Atmospheric Chemistry Program" in this report), but correlation with gust probe data will have to be completed to determine the success of this effort.

Final analysis of data acquired in the NARE '92 study will testify to the performance of the airborne application of the TAGA, but preliminary results indicate that a number of species were detected at varying concentrations, and expected correlations/

discrepancies with measurements from other instruments were observed. At this time, it appears that the TAGA has performed successfully in its first field use. Future applications in the NARE field studies and inflow studies in the eastern Pacific are expected. Although the TAGA is not uniformly sensitive to all chemical species, its addition to the airborne measurement instrument ensemble may be of great benefit to studies in the atmospheric sciences.

Future Requirements/Applications

Operation of the G-1 aircraft in the 1992 ACP field program was not without problems. The large payload of diversified instrumentation employed in the NARE '92 flights dissipated much heat into the aircraft cabin. During G-1 operations in the lower troposphere, in which the aircraft was used in an unpressurized configuration, the air-conditioning system was ineffective. This system was designed to heat and cool the aircraft cabin in a pressurized configuration while operating at higher altitudes. At lower altitudes during the early days of the field study, some instruments malfunctioned because of the excessive cabin temperatures. Some innovative modifications that introduced additional ambient air into the cabin overcame this problem for the most part, at least for flights in relatively cloud- or weather-free situations. Continued use of the TAGA and other power-intensive instruments will require the design and implementation of improved cabin cooling techniques if we are to operate in a wide variety of meteorological conditions.

Preliminary tests conducted during the NARE '92 field program indicate that the TAGA might be successfully operated in a pressurized aircraft cabin by ensuring an airtight sampling train from inlet to exhaust. Additional testing will verify the suitability of using the TAGA at higher altitudes in the troposphere attainable by the G-1 aircraft (about 9 km). The high sensitivity of the TAGA may enable real-time measurements to be made of specific species at higher elevations; such measurements were previously unattainable by other techniques.

It is expected that in support of ACP objectives, the G-1 aircraft will play a key role in the 1993 NARE multiagency, multiaircraft field study in the North Atlantic. The knowledge of operations and instrument validation achieved during the 1992 experiment should enhance performance and improve data quality in 1993.

Funding permitting, in support of other studies related to 'Natural Variability and Anthropogenic Perturbations of the Marine Atmosphere' (see "The 1992 Atmospheric Chemistry Program" in this report), the G-1 aircraft will participate in a field program in the western Pacific to develop a regional chemical climatology to assess the effects of power production-related emissions from the Pacific Rim countries.

With instrumentation and activation of the first Clouds and Radiation Testbed (CART) site in the southern United States Great Plains, it is anticipated that activities in support of the Atmospheric Radiation Measurement (ARM) program may use the G-1 aircraft to supplement surface site measurements with airborne measurements. Instrument systems on the G-1 aircraft are being upgraded to provide improved cloud physics measurements. These upgrades include improved instruments for measuring dew point and cloud liquid water content, upward and downward radiation thermometers, and a two-dimensional greyscale optical particle probe for imaging cloud droplets and ice crystals.

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ASCOT Program Scientific Direction

J. C. Doran

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

In mid-FY 1992, responsibility for the APSD project passed from C. E. Elderkin to J. C. Doran, although Dr. Elderkin has continued to remain active in the project during the ensuing transition period. Principal activities for the year included

- a meeting of ASCOT participants in the fall of 1992
- development and publication of a multiyear strategic plan for the ASCOT program
- establishment of a close working relationship with scientists at DOE's Rocky Flats Plant (RFP)
- analyses of case studies selected from the 1991 winter tracer experiment near RFP, and preparation of a paper outlining ASCOT activities for a Commission of the European Communities (CEC) workshop.

ASCOT Science Team Meeting

A meeting was organized for all ASCOT scientists in November 1991 near Seattle, Washington. Participants showed results of their work using the data collected during the 1990 Oak Ridge and 1991 Rocky Flats experimental campaigns. Numerical modelers described initial efforts to simulate the dispersion of tracers near the RFP in 1991, and simulations of wind fields in the Tennessee Valley during the 1990 experiment. Analyses of Tennessee Valley climatology and wind field variability, and descriptions of the complex layered structure of winds near Colorado's Front Range were also presented. In addition, extensive discussions were carried out on future directions of the ASCOT program.

Multiyear Strategic Plan

A follow-up meeting with a smaller number of scientists was held in Germantown, Maryland, in December to pursue further the issue of future ASCOT activities. The discussions formed the basis for subsequent planning and development, which culminated in May 1992 with the submission of a multiyear strategic plan for the ASCOT program to DOE for review; it was subsequently published by DOE in July. The plan presents an outline for ASCOT research over the next several years in the Oak Ridge and Rocky Flats areas, and indicates future areas for investigation over a longer time. It also provides the basis for increased involvement with university researchers.

Coordination with Rocky Flats Plant Scientists

The tracer releases conducted at the RFP in the winter of 1991 and the coincident meteorological measurements obtained by ASCOT scientists have provided the basis for a continually improving working relationship with RFP personnel. In FY 1992, several meetings were held to explore additional means by which the complementary efforts of RFP and ASCOT scientists could be encouraged. Although formal agreements are not generally anticipated from such meetings, discussions on mechanisms for data exchange, cooperative analyses, attendance at scientific meetings and workshops, and instrument deployment have been beneficial to both parties.

CEC Workshop Paper

A paper analyzing the meteorology during the first of the 1991 tracer experiments was prepared and accepted for presentation at the CEC Third International Workshop: Decision Making Support for Off-Site Emergency Management (Elderkin and Gudiksen 1992). This paper summarizes some of the findings from ASCOT modeling and observations in Colorado's Front Range, and points out some of the relative strengths and limitations of prognostic and diagnostic models for emergency response applications.

Future Studies

Additional analyses of one or more selected cases from the 1991 winter experiment will be carried out, and a paper describing the results will be prepared. In addition, an ASCOT report will be prepared describing the collection of measurements obtained by ASCOT participants in the 1991 winter experiment. A meeting of ASCOT scientists was held in February 1993 to report on current research and to establish plans for an extended measurement campaign using sodar and radar profilers in the Front Range area. A Science Oversight Group will be formed, consisting of scientists outside the DOE ASCOT program, to critically review the activities and direction of the ASCOT Program. In the past, such a group provided valuable feedback to ASCOT scientists on their work, but it has been inactive recently. Preliminary work will be carried out to establish an implementation plan for multiyear ASCOT activities, with initial emphasis devoted to identifying functions, such as operating a data network or archiving data, to be carried out by an ASCOT "infrastructure." Finally, support will be provided to NOAA's Wave Propagation Laboratory to operate a 915-MHz radar wind profiler in South Boulder Creek as part of a planned ASCOT network of profilers and sodars.

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Coupling/Decoupling of Synoptic and Valley Circulations

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, the driving forces, and the interactions of thermally developed complex terrain circulations of different scales. These complicated interactions represent significant challenges that are being met with an integrated program of new field investigations, data analysis from 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 measurement 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 multilaboratory program and is closely coordinated with two other ASCOT programs at Pacific Northwest Laboratory (PNL), the Atmospheric Diffusion in Complex Terrain (ADICT), and the Direct Simulation of Atmospheric Turbulence (DSAT) programs. Numerous data sets support the research, including data collected in ASCOT field programs. In addition, recent research has used meteorological data from many sources to aid in interpretation and hypothesis testing for ASCOT results. In the last year, special research investigations have been focused on a large meteorological data set collected in the complex terrain of the American Southwest.

FY 1992 Results

In FY 1992, work included the analysis and modeling of synoptic/valley wind relationships in the Tennessee Valley, analysis of basin meteorology in the southwestern United States, investigation of pollution transport characteristics in complex terrain areas, and the processing and analysis of data from the ASCOT Front Range Experiment in Colorado. These topics are discussed in more detail below.

Oak Ridge Wind Climatology

The climatology of valley and synoptic-scale wind system interactions was investigated in the Tennessee Valley with a new climatological approach that uses joint wind direction frequency distributions (rawinsonde-measured above-valley winds versus valley winds) to identify key coupling mechanisms. Initial results were obtained in FY 1991 using rawinsonde data and wind data from a tower at Oak Ridge, Tennessee. In FY 1992, analyses were extended to other parts of the valley using 5 years of hourly data from three 100-m towers operated by the Tennessee Valley Authority. Tennessee Valley winds were found to be light and bi-directional, with winds blowing up and down the valley's axis. The bi-directional wind system is not primarily thermally driven, but driven by the along-valley component of the synoptic-scale pressure gradient. The implications of this pressure-driven channeling were investigated further with climatological analyses and with numerical modeling, in cooperation with PNL's DSAT program. The modeling efforts were focused on the coupling mechanisms and the effects of topographic features. The key research results have been communicated to Oak Ridge National Laboratory, where they will be incorporated into their emergency response modeling program. The results were also presented at the Sixth Conference on Mountain Meteorology in the fall of 1992, and a journal article is being prepared.

Wintertime Meteorology in the Colorado Plateaus Basin

The meteorology of basins in the western United States was investigated using wintertime data from the Grand Canyon region. FY 1992 analyses focused on the buildup and breakdown of basin temperature inversions, the development of local and regional topographic circulations, and the influence of synoptic-scale pressure systems on basin wind systems.

Strong temperature inversions are frequently found at the rim level in the Grand Canyon. Analyses of wintertime data from a field experiment near the Grand Canyon in 1991 showed that these sharp elevated inversions represent the boundary between cold air that collects below the rim level in the Colorado Plateaus Basin to the east of the Grand Canyon, and warmer air that is advected over the basin as high pressure ridges approach from the west. Further analyses showed that the elevated inversions can be destroyed and the basin's atmosphere can be ventilated when cold air is advected above the basin with the approach of synoptic-scale, low pressure troughs.

The cycle of cold and warm air advection caused by passing synoptic-scale disturbances provides a mechanism for the destruction of persistent wintertime inversions in basins of the western United States and has important implications for air pollution dispersion. A conceptual model of the inversion destruction mechanism was developed in FY 1992 and was presented at the Sixth Conference on Mountain Meteorology in the fall of 1992.

Dispersion Meteorology of Valleys and Basins

A method to quantify pollutant recirculation and ventilation within a complex terrain region has been developed and applied to data from a network of towers and remote sensing devices (Doppler sodars and radar profilers) in the southwestern United States. Some useful extensions to this approach were developed in FY 1992 and are being investigated further in cooperation with PNL's ADICT program. Data sets from other regions of the country will be processed to test the method. The technique was presented at the Sixth Conference on Mountain Meteorology in the fall of 1992, and a journal article is being prepared.

Front Range Studies

The Coupling/Decoupling program participated in the ASCOT 91 meteorological and tracer experiments in Colorado's Front Range, and has supported the continued development of a meteorological network in the region around DOE's Rocky Flats Plant. Processing and analysis of these data were continued in FY 1992 as new data were added to the central data base. A minisodar was operated in a drainage area to the east of the Rocky Flats plant in cooperation with the DSAT and ADICT programs. Analysis of wind data from a network of towers operated by Lawrence Livermore National Laboratory was also completed. This analysis found that mountain-plain circulations are prominent in the Rocky Flats area, but are frequently affected by overlying synoptic-scale circulations. The results of these analyses will be used to plan for the deployment of other meteorological instruments in the summer of 1993. The

Coupling/Decoupling project will continue to participate in long-range scientific and experiment planning for the ASCOT program.

Other Technical Progress

Several collaborative efforts with other DOE laboratories and universities were begun in FY 1992. Dr. Markus Furger from Switzerland's Paul Scherrer Institute began a one-year visiting scientist appointment and is investigating the use of radar profiler/ radio-acoustic sounding system (RASS) networks for atmospheric mass and heat budget studies. This work is being done cooperatively with C. D. Whiteman (PNL), J. M. Wilczak (National Oceanic and Atmospheric Administration/Wave Propagation Laboratory), and R. Grossman (University of Colorado). Dr. R. K. Hauser from the University of California at Chico visited the laboratory during the summer of 1992 and worked in the DECUP program investigating the development of plain-basin wind circulations over a mountain pass, using data from the Grand Canyon region. Dr. J. Bossert and G. Poulos from Los Alamos National Laboratory began a cooperative effort with C. D. Whiteman to model the synoptic-scale influences on the flow along a valley that connects a plain to a basin. Observations of flow in the Grand Canyon heightened the interest in this joint project. Over the last few years, the DECUP program has provided partial support for K. J. Allwine's Ph.D. program at Washington State University; several publications resulted from this completed work in FY 1992. Finally, surface energy budget measurements collected with a new instrument as part of the DECUP program in 1991 resulted in a publication produced in cooperation with DOE Atmospheric Radiation Measurements (ARM) investigators.

Future Research

In FY 1993, the work reported above will be extended, and journal articles will be submitted for publication. Future work will concentrate on valley and basin meteorology, including field modeling investigations of the energetics of valley and basin atmospheres, the development of local wind systems and the influence of synoptic-scale flows, the buildup and breakdown of basin inversions, the development of mountain-plain circulations, and the transport and diffusion of air pollutants in areas of complex terrain.

Atmospheric Diffusion in Complex Terrain

K. J. Allwine and J. M. Hubbe

The purpose of the Atmospheric Diffusion in Complex Terrain (ADICT) program is to develop an understanding of the physical processes governing atmospheric transport and diffusion in complex terrain, and to describe these processes with appropriate numerical and/or conceptual models. Such models are required for realistically assessing potential and actual environmental impacts arising from use of energy resources, and for analyzing and predicting the fate of pollutants released routinely or accidentally into the atmosphere. In addition, this understanding can lead to parameterizations of subgrid-scale exchange processes in regional-scale to global-scale models.

The objectives of the ADICT program include 1) identification of the forcing mechanisms responsible for the observed wind, turbulence, and temperature structures in complex terrain; 2) analysis and application of field and numerical model data to assess the relative importance of such mechanisms and their effects on atmospheric transport and diffusion; 3) development, testing, and application of numerical and conceptual models capable of describing and predicting the behavior of the winds, temperatures, and atmospheric constituents in regions of interest; and 4) presentation of results at scientific meetings and in peer-reviewed journals.

The ADICT program maintains an integrated approach for accomplishing its research objectives, which includes field observations, data analysis, theoretical investigations, and numerical modeling. The research undertaken during FY 1992 has added to our basic knowledge of transport in the atmospheric boundary layer, led to an improved understanding and modeling of atmospheric dispersion in mountain valleys and basins, and contributed to understanding the interaction of ambient and locally generated wind systems and their effect on dispersion. Specific accomplishments during FY 1992 are

- The research on identifying and characterizing the physical processes dominating dispersion in valleys and basins was published (Allwine

1992a; Allwine et al. 1992), presenting the results from the 1984 Atmospheric Studies in Complex Terrain (ASCOT) Brush Creek Valley experiment, and the results of a tracer experiment conducted in the Roanoke Basin of Virginia. A dissertation presenting research conducted in conjunction with the Coupling and Decoupling of Local and Synoptic Circulations (DECUP) program was also published (Allwine 1992b).

- A major meteorological and tracer field experiment was successfully conducted on the Hanford Site diffusion grid. The primary objective of the study is to identify how large an upwind source area (source footprint) contributes to the trace gas flux at a downwind point a few meters above the Earth's surface, and to understand and describe the basic relationships between the source area and flux measurement.
- Analyses were begun on the meteorological data collected during the 1991 ASCOT Front Range study. A minisodar measuring winds was operated continuously near the Rocky Flats Plant in a joint effort with the Direct Simulation of Atmospheric Turbulence (DSAT) and DECUP programs.
- Mathematical definitions of atmospheric stagnation, ventilation, and recirculation applicable to single-station wind measurements were developed in conjunction with the DECUP program (Allwine and Whiteman 1992). These measures of atmospheric transport characteristics are especially suitable for use with new ground-based remote wind profiling sensors.
- A student in DOE's Science and Engineering Research Semester (SERS) program was hosted for a 6-month appointment at PNL. This student helped with the analysis of the data from the 1991 ASCOT Front Range Study.

Detailed descriptions of the principal accomplishments are given below.

Valley Ventilation and Dispersion Study

The concept of a valley being treated as a subgrid-scale line-source of pollution in regional-scale dispersion models is supported from analyses of the tracer and meteorological data collected during the 1984 ASCOT study conducted in Colorado's Brush Creek Valley. The results of the analyses were completed and published (Allwine 1992a,b). The principal findings were that tracer released near the valley floor did not reach the ridge tops (escape from the valley) during the night, but was confined to the valley and carried in down-valley flows. After sunrise, with the onset of convective boundary layer growth and initiation of upslope flows, the tracer within the valley was carried into the upper elevations of the atmosphere and ventilated from the valley. This was confirmed by observations of tracer after sunrise at the ridge top tracer samplers and by a tracer mass budget applied to a valley atmosphere control volume. The ventilation rate of tracer from the valley atmosphere to the above-ridge top flows was calculated from the tracer mass budget. A dimensionless form of the ventilation rate was developed:

$$\frac{Q_v \tau}{Q_s / U_T} = 6.91 e^{-3.89\frac{t}{\tau}} \sin\left(\pi \frac{t}{\tau}\right) \quad (1)$$

where Q_V is the valley ventilation rate ($gs^{-1}m^{-1}$), U_T is the mean down-valley wind speed (ms^{-1}), Q_s is the source release rate (gs^{-1}), τ is the time between sunrise and the breakup of the temperature inversion in the valley (s), and t is the time after sunrise (s). The constants on the right-hand side of Equation (1) were determined from an empirical fit to the data. Equation (1) may be generally applicable for representing the ventilation of material from ground-level releases in a valley during the morning transition period; however, more work will be required to verify this.

The tracer plume from the ground-level release in the Brush Creek Valley remained fully contained in the near-steady down-valley flows during the night. The Gaussian plume equation adequately represented (16% average deviation) the average night plume center line concentration at ground level, out to 8 km from the release. This agreement was attained by accounting for plume reflections from the valley sidewalls and using measured turbulence statistics in calculating the dispersion coefficients. Beyond 8 km down-valley from the release, the Brush Creek Valley merged with the Roan Creek Valley and the two air streams mixed, resulting in a sudden dilution of the tracer plume. The Gaussian plume equation was not valid after the two air streams merged. These applications of the Gaussian plume equation indicate that this equation is a reasonable "model" of atmospheric diffusion, even in complex terrain, under certain limited meteorological conditions; however, it is not appropriate for general use in complex terrain.

Basin Wintertime Stagnation Study

Atmospheric dispersion in basins is not well-understood. During the wintertime, atmospheric stagnation episodes can result in unusually high concentrations of air contaminants near ground level. During January 1989, a meteorological and tracer experiment was conducted by the EPA in a Virginia basin. This study was designed to help identify and understand the dispersion characteristics of a basin atmosphere during winter stagnation conditions. The basin studied was the Roanoke Basin located on the eastern slope of the Appalachian Mountains. The data from this study were analyzed and the results published (Allwine 1992b; Allwine et al. 1992). The principal finding was that the formation of a cold-air pool was the dominant mechanism governing the general structure of the wind and temperature fields in the Roanoke Basin. The transport and diffusion of air pollutants was strongly dependent on the location of the plume relative to the top of the cold-air pool.

A simple model, based on air mass continuity, of the cold-air pool formation was developed:

$$\int_0^{H_{ca}} A_b(z)dz = \int_0^{t_{ca}} \Psi_s(t)dt \qquad (2)$$

where $H_{ca}(t)$ is the height of the top of the cold-air pool (m), $A_b(z)$ is the horizontal area of the basin as a function of height (m^2), z is the vertical coordinate with its origin at the lowest point in the basin, $\Psi_s(t)$ is the volume flow rate of air accumulating in the basin (m^3/s), and t_{ca} is elapsed time (s). Initially, H_{ca} is zero when t_{ca} is zero. The maximum value of H_{ca} is constrained to be less than, or equal to, the height of the lowest outflow barrier in the basin. The maximum value of H_{ca} is expected to depend on atmospheric stability and wind strength above the cold-air pool. The volume flow rate of air accumulating in the basin can be determined from observations of slope flow strengths and depths, or from slope flow models. The horizontal area of the basin as a function of height can be determined from topographic maps or digital terrain database.

The specific results from the Roanoke Basin analysis showed that a cold-air pool formed in the basin, beginning after the evening transition period, and filled to near the elevation of the lowest mountain barrier. A sharp potential temperature jump was present at the top of this fully developed cold-air pool. Vertical measurements of tracer concentration showed the initial ground-level plume to become elevated and ride over the top of the cold-air pool. Horizontal plume spread was enhanced over that expected from turbulent diffusion alone, by shear in wind direction vertical profiles. The tracer concentrations within the cold-air pool increased slowly with time, even after the release was terminated. After sunrise, the elevated plume appeared to mix to the ground.

Front Range Study

Analysis of the meteorological data collected during the Colorado Front Range experiment near the Rocky Flats Plant was begun, as was analysis of the tracer data collected by Rocky Flats Plant personnel and contractors. The primary goal of these preliminary analyses will be to identify and characterize the dominant physical processes governing dispersion in the study region. A secondary goal will be to begin characterizing the climatology of this portion of Colorado's Front Range, using the continuously collected data from the meteorological network in the area.

Under a joint effort with the DECUP and DSAT programs, the PNL minisodar near the Rocky Flats Plant continued to operate and collect profiles of wind data. These data were assessed for quality, archived for distribution to other researchers, and used in the above-mentioned analyses.

Source Footprint Experiment

The ADICT program hosted a major atmospheric field experiment conducted on the Hanford Site's diffusion grid, involving 18 scientists and engineers. The principal investigators for the experiment were from Washington State University (WSU) and the National Center for Atmospheric Research (NCAR), under funding from the National Science Foundation. Other participants were from the University of Quebec at Montreal and the U.S. Environmental Protection Agency's Environmental Research Laboratory at Corvallis, Oregon. From

May 25 to July 3, 1992, more than 200 hours of atmospheric tracer data and a continuous record of meteorological data were collected. The data will be used to address the overall scientific objectives of this basic research program: identifying how large an upwind source area (source footprint) contributes to the trace gas flux at a downwind point a few meters above the earth's surface, and understanding and describing the basic relationships between the source area and flux measurement. The results from this research program will enhance our understanding and description of the exchange of heat, moisture, and gases between the earth's surface and the atmosphere. This information will be useful in the development of improved mathematical relationships for treating the surface-atmosphere exchange processes in meteorological models.

The ADICT program will benefit from its access to this unique data set that applies to studies of the atmospheric diffusion process near the earth's surface. One focus in the ADICT program is simplifying the measurement of the ground heat flux component of the surface energy balance. A method has been developed for determining the ground heat flux at the surface by using only measurements of soil temperature at various depths, and soil thermal conductivity at one depth. The volumetric heat capacity and thermal conductivity of the soil column are calculated from the soil temperature profile and the one-dimensional heat conduction equation. These soil properties do not have to be measured, thus simplifying the determination of the ground heat flux at the surface.

Future Studies

A paper detailing the mathematical definitions of atmospheric stagnation, ventilation, and recirculation applicable to single-station wind measurements will be prepared and submitted for publication. This paper will give example "signatures" of the integral quantities for various types of landforms (e.g., valleys, basins, and slopes). This research is being conducted in conjunction with the DECUP program.

The approach for determining the ground heat flux at the surface from soil temperature profile data will be finalized and submitted for publication. Several data sets, including that from the " source footprint" experiment, will be used to test the approach. The application of this approach will simplify the measurement of ground heat flux, which is a component of the surface energy balance.

The analyses of the data from the Colorado Front Range study will continue. The analysis will focus on: 1) identifying the interaction of the drainage from the Coal Creek Canyon with the winds over the Rocky Flats facility and the winds within the Standley Lake air shed (toward Denver), and 2) establishing the climatology of this Front Range region. The overall goal is to identify the dominant physical processes governing dispersion in the area of the Front Range, and identify the frequency of their occurrence.

The continuously collected minisodar data will be made available to the ASCOT community. A field study of the Eldorado Canyon drainage will be planned and implemented. In addition, a Front Range regional drainage/interaction field study will be planned for implementation during FY 1994. This research will be conducted in conjunction with other ASCOT programs.

Preliminary work will begin on applying parallel processing technology to Lagrangian diffusion modeling. A parallel processing computer will be purchased, and programming will begin. The goal is to begin applying parallel processing technology to emergency response needs.

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Interactions Between Surface Exchange Processes and Atmospheric Circulations (IBSEPAC)

W. J. Shaw and J. C. Doran

The purpose of the Interactions Between Surface Exchange Processes and Atmospheric Circulations (IBSEPAC) program is to improve our understanding of the interactions between surface fluxes of heat, momentum, and moisture, and the structure of the atmospheric boundary layer. The objectives of the program are 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.

Recent Progress

A three-phase field experiment that investigated boundary layer fluxes over a mixed sagebrush canopy was carried out on the Hanford Site in FY 1992. This initial work specifically addressed objectives (1), (2), and (5) stated above. The observations focused on defining the surface layer turbulence fluxes via the eddy correlation technique, and establishing the energy balance within the vegetation canopy. The latter is important because vegetation provides a significant feedback for surface heat and moisture fluxes that are currently crudely approximated in model parameterizations.

Three intensive operation periods (IOPs) contained the bulk of the measurements. The IOPs were each approximately one week long and occurred in March, April, and May, thereby spanning the "dry-down" portion of the annual cycle. Four categories of measurements were made: twice-daily radiosonde profiles; continuous eddy-correlation measurements of momentum, heat, water vapor, and CO_2 fluxes; remote and in situ surface-energy budget measurements; and plant and soil status measurements.

Eddy correlation measurements of surface layer turbulence fluxes were made at approximately 5 m aboveground. Wind velocity components and virtual temperature were measured using a sonic anemometer. Temperature was measured with a fast-response platinum-wire resistance thermometer. An infrared absorption instrument was used for high-speed measurements of both CO_2 and water vapor. For reference purposes, independent measurements of wet- and dry-bulb temperature, and wind speed and direction were made with a sampling frequency of 1 Hz. This suite of instruments ran continuously during each IOP.

The eddy correlation measurements integrated the energy fluxes from surfaces that were from 60 to 300 m upwind of the sensors. Three distinct surface conditions exist within this measurement footprint: bare soil, soil covered predominantly by cheatgrass, and large sagebrush as tall as 2 m. The soil was a loamy sand approximately 70 to 90 cm deep, overlying gravels. Soil moisture values ranged between 16% and 0.5% by weight, with most samples ranging within 4% to 7%. Measurement arrays included thermocouples for soil and vegetation temperatures, and sensors for infrared surface temperature, downwelling and upwelling visible irradiance, net radiation, soil heat flux, and rainfall. These were operated continuously between March 18 and May 27. Soil thermoconductivity and soil water potential measurements were also made during most of this period. Vegetation was characterized twice and included estimates of cover, biomass, sagebrush height and width, leaf conductance, and leaf water potential.

Plans for FY 1992 also included the procurement and setup of a 915-MHz wind profiling radar with radio-acoustic sounding system (RASS). Radar delivery was anticipated for May 1992 but did not occur until early October. This trailer-mounted system is currently being installed at the Hanford Meteorological Station and will be used in the IBSEPAC project in FY 1993.

Future Plans

During FY 1993 analysis of the data collected in the FY 1992 field experiment will continue, and a journal article describing the results will be prepared. Additional measurements may be taken to include time periods of interest that were not covered in the initial work. Detailed comparisons of the observations will be made, with predictions obtained from one or more surface energy balance algorithms. An effort will be made to identify a minimum set of parameters that must be measured to obtain reliable estimates of surface fluxes of heat and moisture in semiarid conditions.

A critical examination of techniques that are used to obtain heat and moisture fluxes over semiarid terrain will also be started. A number of comparisons of eddy correlation and Bowen ratio measurements have been made in the past, but most of these were conducted in environments considerably wetter than that of the Hanford area. To address this problem, we will use the data collected in this project's field experiments as well as other data obtained from DOE's Atmospheric Radiation Measurements (ARM) program. We will assess the accuracy with which flux measurements can be made, particularly as soils dry during late spring and early summer.

Work will also continue in developing the newly acquired wind profiler/RASS for observing the structure of the boundary layer. Validation of the system's measurements of wind and temperature will be completed using the Hanford meteorological tower and other available facilities. Initial efforts will also be made to obtain and verify momentum and heat flux profiles from the system. Profiler measurements at the Hanford tower, and later at other locations, will be coordinated as early as possible with the surface observational component of this program. Emphasis will be placed on using the profile information to increase our understanding of the physical processes that produce variations in subgrid-scale surface flux measurements and our ability to identify the important parameters for these processes.

Finally, in FY 1993 we plan to procure and make initial measurements using an optical scintillometer. This device uses principles of similarity theory applied to turbulence-induced refractive index variations to provide path-averaged measurements of surface heat flux. Such observations will provide an additional means to assess area-averaged fluxes.

Direct Simulation of Atmospheric Turbulence

J. C. Doran

The objective of the Direct Simulation of Atmospheric Turbulence (DSAT) project is to use advanced numerical models to simulate complex nonlinear dynamics in atmospheric flows. Additionally, in cooperation with other PNL programs, the DSAT project jointly supports activities of the U.S. Department of Energy's (DOE) Atmospheric Studies in Complex Terrain (ASCOT) program in experimental and analytical studies of atmospheric dynamics and their effects on diffusion of atmospheric pollutants. In FY 1992, principal accomplishments of DSAT included

- continued support of J. Barnard's graduate research program in numerical simulations of stable turbulent boundary layer flows
- support (with two other ASCOT projects) for operation of a minisodar near the Rocky Flats Plant (RFP) adjacent to Colorado's Front Range
- numerical simulations of the interaction of ambient and valley winds in the Tennessee Valley
- acquisition and initial application of the Colorado State University Regional Atmospheric Modeling System (RAMS) mesoscale model
- identification and initial collection of data sources for analysis of regional drainage flows in the Pacific Northwest

- partial support for a post-doctoral appointment in the Atmospheric Physics Group at PNL.

Simulation of Turbulence in Stably Stratified Flows

The DSAT program has supported work by J. Barnard at the University of Washington that is aimed at understanding the turbulent dynamics of stable flows in the atmosphere. In FY 1992, a numerical technique developed by Spalart et al. (1991) was applied to study the stability of laminar-turbulent transitions in a stratified Ekman layer. The technique appears to hold considerable promise: it produced good agreement with previous results obtained for neutral layers and it also revealed inadequacies in the treatment of stable layers by earlier investigators. Significant progress was also made toward the development of a full three-dimensional code to simulate turbulence in sloping stable boundary layers.

Minisodar Operation

The ASCOT program is currently focusing on the Front Range area of Colorado, near DOE's RFP. As part of the effort to assess the importance of drainage winds emanating from canyons in the Front Range west of the RFP, PNL has operated a minisodar for over 1 year in an area just southeast of the RFP and roughly in line with the outflow from Coal Creek Canyon. The objective is to collect sufficient data to establish a local "climatology" of the winds in the area of the minisodar and to correlate them with the occurrence of drainage winds in the canyon that have been monitored by a second minisodar operated by Argonne National Laboratory. The DSAT program has supported this data collection effort during the past year in cooperation with two other PNL ASCOT projects (Coupling/Decoupling of Synoptic and Valley Circulations [DECUP] and Atmospheric Diffusion in Complex Terrain [ADICT].

Simulations of Tennessee Valley Winds

A series of numerical simulations was carried out to assess the importance of various forcing mechanisms that determine wind direction in the Tennessee Valley. The work was carried out jointly with another PNL ASCOT project, DECUP, which used upper-air and tower data collected over a 5-year period to establish the joint frequency distribution of 850-mb and 100-m winds in the Tennessee Valley. Several processes were suggested to account for the observed distribution; numerical modeling was designed to test the effects of the proposed mechanisms. Agreement between simulated and observed behavior is generally good. Model results have revealed additional features that may also contribute to the observed behavior of the valley winds. A paper describing the results obtained thus far was presented at the Sixth Conference on Mountain Meteorology in Portland, Oregon in October 1992.

Mesoscale Model

The Colorado State University RAMS mesoscale model was purchased and installed on a SUN work station. The model is a fully elastic, nonhydrostatic code that features interactive grid nesting for resolving small-scale features of terrain and meteorological fields. Initial tests of the model were carried out using terrain files for the region encompassing Colorado's Front Range. Initial simulations have begun to analyze the behavior of large-scale (~100 km) drainage flows down the South Platte River Valley. This drainage passes through Denver and near the RFP, and is believed to be an important factor in regional and local air quality issues.

Regional Drainage Flows in the Pacific Northwest

During the late spring and summer months, the Hanford Site often experiences strong winds from the northwest. These winds may blow for a few hours or persist through the night. The winds appear to be related to the presence of a deep marine layer to the west of the Cascades and strong heating to the east; a detailed study of the phenomenon has not been done. Preliminary computer simulations were performed in FY 1992 with some success, but a detailed comparison with data has not been carried out. Data sources in addition to the Hanford meteorological network have been identified; data collection and initial analyses were begun for several drainage wind cases.

Post-Doctoral Support

Dr. Shiyuan Zhong completed her Ph.D. requirements at Iowa State University in the summer of 1992 and began a one-year Northwest Organization of Colleges and Universities for Science

(NORCUS) post-doctoral appointment in late FY 1992. The DSAT program is sharing the cost of her tenure at PNL with another DOE research project.

Future Studies

In FY 1993, work on the forcing mechanisms of the Tennessee Valley winds will conclude and a paper will be submitted to a refereed journal for publication. Support will continue for J. Barnard's graduate program in the numerical simulation of turbulence in stably stratified flows, and it is expected that his dissertation research will be substantially completed during this period. A major effort will be devoted to learning more of the features of the RAMS model and applying it to simulations of drainage flows in the South Platte River Valley. The work will be done in cooperation with scientists from NOAA's Wave Propagation Laboratory, who have access to lidar measurements for comparisons with simulated flow patterns. Studies of regional drainage flows in the Pacific Northwest will also be carried out using both observations and numerical modeling.

The PNL ASCOT projects are also exploring options for installing additional instruments in the Front Range of Colorado to expand the scope of the studies being conducted there. The DSAT program will support such efforts, which are expected to include deploying a sodar and 915-MHz profiler in the area during the summer of 1993.

Reference

Spalart, P. R., R. D. Moser, and M. R. Rogers. 1991. "Spectral Methods for the Navier-Stokes Equations with One Infinite and Two Periodic Directions." *J. Comput. Phys.* 96:297-324.

Climate
Research

CLIMATE RESEARCH

Climate change research at the Pacific Northwest Laboratory (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 Measurement (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 CO_2. 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.

Research on greenhouse gas emissions continues to improve the reliability of forecasts of emissions of CO_2 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. 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.

As part of the U.S. Department of Energy's (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.

Advances have been made in the treatment of clouds in general circulation models. Efficient parameterization of stratus cloud microphysics have been incorporated in a climate model. Improvements to climate models that are gained through advances in our understanding of the chemistry and physics of the climate system are being integrated with the rapid pace of advances in computer technology.

Ocean research related to climate change examined ocean mixed-layer dynamics, deep convection, and ocean circulation and climate modeling. PNL is working to improve the parameterizations of the dynamics of the surface mixed layer, transport through the thermocline, and formation of deep water.

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

- **Atmospheric Radiation Measurement Program**
- **Characterization of Cloud/Aerosol Interactions with Solar and Long-Wave Radiation**
- **General Circulation Models**
- **Photometric Studies of Clouds from an Atmospheric Radiation Measurement Site**
- **Second Generation Model**
- **CO_2 Ocean Research**
- **Ocean General Circulation Models.**

The Atmospheric Radiation Measurement (ARM) Program: Field Measurements for Radiation Forcing and Feedbacks in General Circulation Models

T. S. Cress and G. M. Stokes

Atmospheric general circulation models (GCMs) are useful tools for advancing our understanding of the global climate system and the impact that human activities have on it. For instance, how different energy scenarios change the atmospheric concentration of carbon dioxide can be investigated through the use of GCMs. One of DOE's goals is to improve the performance of GCMs as tools for predicting global climate change. To achieve this goal, DOE initiated a multifaceted research program to improve understanding of the physical processes modeled in GCMs that limit GCM performance.

The Atmospheric Radiation Measurement (ARM) Program is the major field portion of DOE's climate change research program. The ARM Program contributes to DOE's goal by concentrating on improving the treatment of cloud radiative forcing and feedbacks in GCMs. These represent the major source of uncertainty in models and the highest research priority identified by the Committee on Earth and Environmental Sciences of the Federal Coordinating Council for Science, Engineering, and Technology.

The experimental objective of the ARM Program is to characterize the radiative processes in the Earth's atmosphere with improved resolution and accuracy. The key research objective is the improved treatment of clouds and radiation transfer in climate models. To address the research objectives and to provide the data required, the ARM Program is composed of three distinct entities: a Science Team, an Instrument Development Program, and the Clouds and Radiation Testbed (CART). Using data provided by CART, the Science Team develops and evaluates improved models and parameterizations for use in GCMs. The Instrument Development Program strives to develop new or improved observational capabilities for the CART where existing capabilities are inadequate or nonexistent.

The design of CART incorporates the following elements:

1. up to five permanent measurement sites composed of a highly instrumented central facility and a surrounding network of sensors to document cloud distribution and morphology in the atmospheric volume above the site
2. a network of surface meteorological observing stations at each of the five sites to document surface meteorological and radiative homogeneity over an area comparable to the computational grid cell of a GCM
3. airborne observations as required for in situ measurements not available from ground-based remote sensors, or for evaluating measurements from ground-based remote sensing instrumentation
4. the acquisition of satellite data from existing operational and research satellites
5. a data system to process and distribute data from the measurement sites and other sources to Science Team members.

The ARM Program involves nine of DOE's national laboratories whose efforts are coordinated through the ARM Program Office at PNL. Participants also currently include seventeen universities, nine government laboratories outside of DOE, as well as foreign national investigators and several domestic companies. Collaborative activities are more extensive.

In FY 1992, the ARM Program began to establish its first site. In parallel, preparation and planning continued for deployment to successive field sites and participation in collaborative efforts. Efforts included

- beginning the phased deployment to the Southern Great Plains site
- establishing the data acquisition and distribution system

- completing agreements for access to data required from other programs and agencies
- establishing procedures to process and deliver data to Science Team members to meet their individual needs.

Key accomplishments include

- approval for the Environmental Assessment for the Southern Great Plains site, with an Environmental Assessment "finding of no significant impact" released by DOE
- initial site occupation and the establishment of initial observing and data communication capabilities, including
  - initial suite of instrumentation
  - site data system
  - mobile shelters for instruments, electronics, shops, and personnel
  - onsite utilities, communications, and preparations for anticipated future instrumentation
- establishment of a central data processing center (the "Experiment Center")
- establishment of an interim data archival capability pending a permanent capability
- establishment of a high-speed data communications link between the field site, the Experiment Center, and the Archive
- delivery of the first data set to a Science Team member
- initiation of the acquisition of satellite data and data from the National Weather Service
- completion of draft on final Experiment Designs for 60% of the Science Team members
- completion of draft Experimental Operations Plans for 30% of the Science Team members
- selection of the Site Scientist for the Southern Great Plains site, and the Site Program Manager for the Eastern North Pacific/Atlantic site
- transition of the multifilter rotating shadowband radiometer from the Instrument Development Program to operational use at the Southern Great Plains site
- initiation of collaboration that will result in measurements of ultraviolet radiation at the ground at the Southern Great Plains site.

Experimental Approach

The ARM Program Plan (DOE 1990) outlines the program's basic experimental approach. Field measurements will be used to initialize the radiation and cloud process models and to provide the data for model comparison and evaluation.

The experimental approach emphasizes three areas of concern: 1) data to evaluate and test radiative models; 2) data to develop and test the performance of radiative parameterizations on the scale of a GCM computational grid cell; and 3) data to characterize the distribution, type, and morphology of clouds to facilitate the development of effective GCM parameterizations for cloud formation, maintenance and dissipation, and cloud impacts on atmospheric short- and long-wave radiation.

Figure 1 shows the general concept of a CART site with its component central facility and auxiliary, extended, and boundary facilities. CART sites will use ground-based in situ and remote sensing instrumentation to document the radiative properties and fluxes at the ground and within the atmospheric column overhead, to document the mean atmospheric properties of the encompassing atmospheric volume representative of a single column of a GCM grid cell, and to document the advection of atmospheric properties (e.g., temperature) and constituents (e.g., water vapor) into and out of the single column grid cell.

Additional data from other programs, such as the National Weather Service and operational and research satellites, will be acquired and incorporated into the ARM data base as required. Airborne measurement platforms will be used to acquire additional in situ data, or to confirm the accuracy of remotely sensed data.

Instrumentation

The measurement strategy necessary to address the scientific questions germane to each locale will determine specific instrumentation requirements

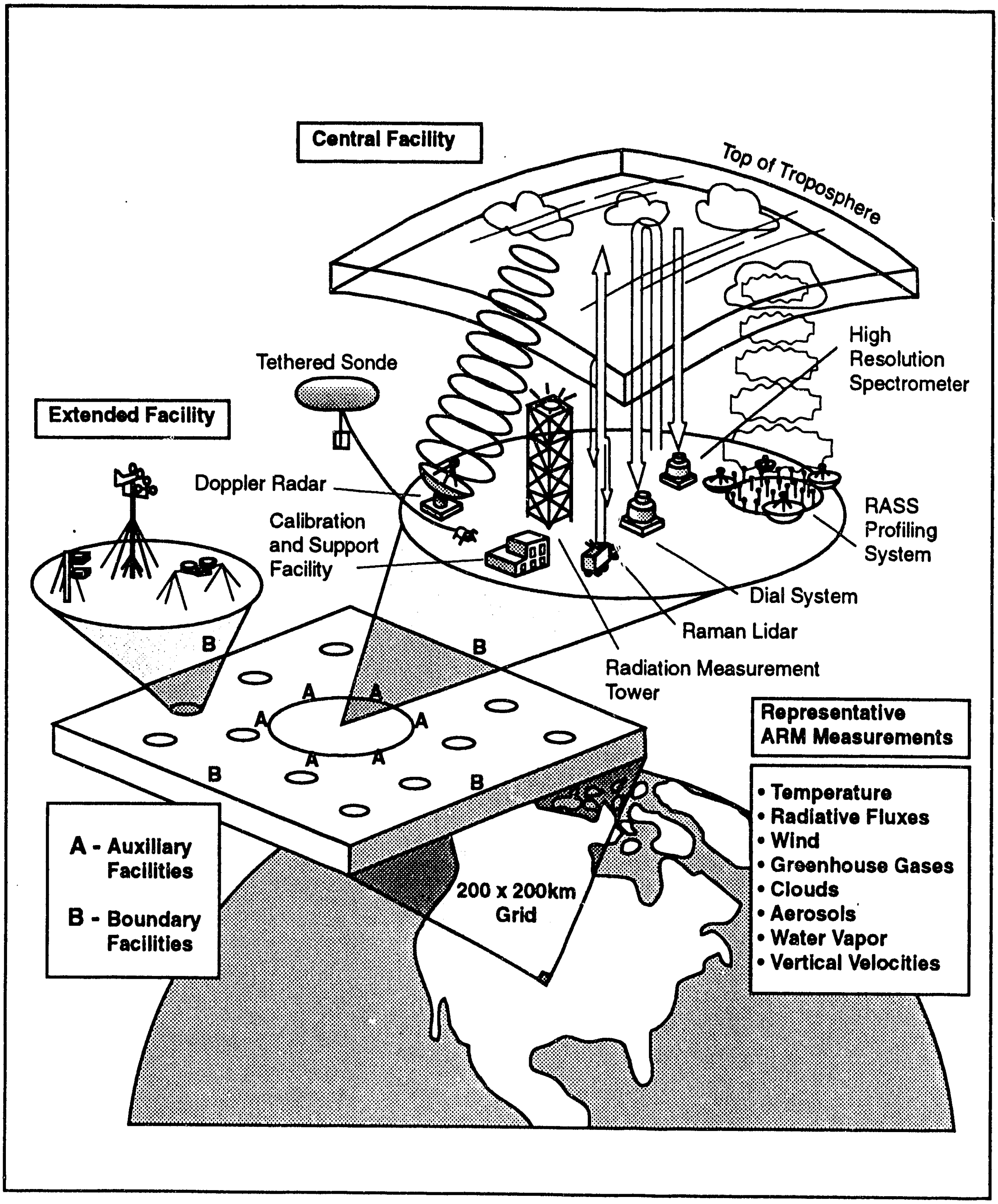

FIGURE 1. Conceptual Diagram of a CART Site.

and deployment. The Southern Great Plains site is the current focus, and the instrumentation requirements and distribution at this site will be similar to the concept depicted in Figure 1. The instrument suites selected and deployed for subsequent sites may vary substantially. Strategies appropriate to the tropical western Pacific Ocean and the North Slope of Alaska are being studied and refined. Some instrumentation for the tropical western Pacific Ocean will be acquired and configured in FY 1993 in preparation for deployment in FY 1994.

The instrumentation for the Southern Great Plains site emphasizes observations made over a land surface and includes sensors to measure air-surface exchange of moisture, heat, and momentum. Balloon-borne sounding systems will document the vertical profiles of wind speed, temperature, and humidity. Other sensors will document integrated columnar amounts of water vapor and liquid, and vertical profiles of mean wind velocity components and temperature. Broadband radiometers will observe upwelling and downwelling radiation as well as direct and diffuse solar radiation. Table 1 lists these instruments and the measurements to be made at each facility.

The Instrument Development Program provides for the development of observational capabilities where they are needed but where none exist, or where current capability is inadequate to the measurement task. Table 1 includes a summary of the instrumentation development efforts that were under way at the beginning of FY 1992. Sufficient progress has been made on developing the laser ceilometer, the infrared interferometer, and the 94-GHz cloud radar to warrant their evaluation at the Southern Great Plains site. Prototype systems are expected to be deployed in FY 1993.

Locale Priority and Status

Locales recommended as long-term measurement sites for the ARM program (DOE 1991) were prioritized based largely on consideration of global climate regimes, but also included consideration of surface homogeneity on the scale of a few kilometers. In 1990, five primary locales were recommended for long-term occupation (7 to 10 years). By priority, these were

1. Southern Great Plains
2. Tropical Western Pacific Ocean
3. North Slope of Alaska
4. Eastern North Pacific (or Atlantic) Ocean
5. Gulf Stream off Eastern North America

This priority was reviewed and accepted in FY 1991 and a specific site was selected in the Southern Great Plains. Deployment of instruments and facilities to the Southern Great Plains site was initiated in FY 1992. Plans call for sites in subsequent locales to be occupied at a rate of one every 18 to 24 months. Although the priority was based partly on the GCM parameterizations to be addressed, each locale is being evaluated for the specific scientific questions raised there, the data required to address those questions, and the feasibility of long-term support of a measurement site. Ocean sites will be particularly challenging and possibly require innovative and more limited strategies.

While the Southern Great Plains was established as the highest priority site based on the range of radiative and cloud conditions, synergistic opportunities, and logistical feasibility found there, subsequent sites were recommended for meeting more sharply defined scientific needs. The key scientific issues to be addressed in the tropical western Pacific Ocean, for example, include the radiative feedback processes involving the extensive cirrus cloud cover generated by deep convection, the radiative impacts of deep cumulus clouds, and the adequacy of GCMs to represent the development, persistence, and advection of clouds and cloud cover over the Pacific Basin. Siting strategies to address the key questions in the tropical western Pacific are being formulated and will be evaluated for deployment decisions in FY 1993. Instrument procurement and facilities development is anticipated to begin in FY 1993.

For the North Slope of Alaska site, environmental concerns about wetlands and wildlife are being examined and siting strategies are being developed for further evaluation. Specific siting decisions are expected to be made several years prior to deployment, which is currently anticipated for FY 1996. The key scientific issues for the North Slope include the annual day-night cycle in the radiative environment, heat and moisture fluxes from the surface, and the impact of Arctic stratus clouds and surface albedo conditions on the radiative environment.

TABLE 1. Instruments by Measurement Facility

	Property Measured
Central Facility Instruments	
915-MHz radar wind profiler with RASS	Vertical profiles of wind velocity components and acoustic virtual temperature in the atmospheric boundary layer.
50-MHz radar wind profiler with RASS	Vertical profiles of wind velocity components and acoustic virtual temperature above the atmospheric boundary layer.
Balloon-borne Sounding System	Wind speed, wind direction, temperature and humidity profiles.
Microwave Water Radiometer	Integrated columnar amounts of water and liquid.
Instrumented 60-m Tower	Eddy correlation measurements of heat, momentum, and moisture fluxes at heights of 60 and 25 m; observations of mean wind components, temperature, and humidity at a height of 60 m; upwelling broadband solar and infrared fluxes at heights of 60 and 25 m.
Calibration Facilities	Absolute radiometer; comparison stand; laboratory components.
Aerosol Instruments	Nephelometer; ozone sensor; CCN counter; aerosol filter pack system with two size cuts; filter sample system for optical absorption; optical particle counting systems.
Instrument Group Identical to Extended Site Facility Instruments	See Extended Site Facility descriptions.
Instrument Development Program	
Ceilometer	Cloud heights including cirrus; aerosol backscatter in the atmospheric boundary layer.
Raman Lidar	Vertical profiles of water vapor and ozone concentrations.
Infrared Interferometer Spectrometer	Infrared radiances at the surface.
35- and 94-GHz Radar Systems	Cloud properties.
Lidar Systems	Aerosol and cloud properties.
Auxiliary Sites	
Whole-sky Imaging System	Mapping cloud geometry; possibly radiance observations.
Extended Site Facilities	
Surface Flux Stations	Vertical fluxes of heat, moisture, and momentum. Energy balance Bowen ratio systems will also observe soil heat flux, soil temperature, and soil moisture, each at one depth.
Wideband Solar and Infrared Sensors; Multifilter Rotating Shadowband Radiometer	Normal incident pyranometer; precision spectral pyranometer; pyrgeometer; pyranometer and pyrgeometer for upwelling irradiance; solar spectral radiometer; upwelling and downwelling irradiances.
Surface Meteorological Sensors	Mean wind speed and direction at a height of 10 m; temperature and humidity at a height of 1.5 m; barometric pressure, and liquid precipitation.
Boundary Facilities	
Collocation with Wind Profilers (some with RASS)	Wind and temperature profiles (with profiler-RASS).
Balloon-borne Sounding System	Wind, temperature and humidity profiles.

For the eastern North Pacific and Gulf Stream locales, activity is limited to analyzing the scientific issues, evaluating the value of ongoing research efforts, and assessing possible deployment strategies in these largely ocean sites.

Southern Great Plains Site Occupation

The phased occupation of the Southern Great Plains site began following the preparation of an Environmental Assessment (EA) in accordance with the National Environmental Protection Act. Based on the EA, DOE approved a "finding of no significant impact" in April 1992.

The Southern Great Plains site (Figure 2) takes advantage of other programs that require data similar to those needed by the ARM Program. For instance, the area selected for the field site is bounded by the densest part of the Wind Profiler Demonstration Network in south-central Kansas and north-central Oklahoma. The central facility will be near Lamont, Oklahoma, close to the center of the Wind Profiler Demonstration Network, while boundary facilities will be located to complement the measurements of other wind profilers. Data from the wind profiler network will be acquired through the National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory in Boulder, Colorado.

Other synergistic opportunities also exist at this site. NOAA's National Severe Storms Laboratory will collaborate with the ARM Program by exchanging recorded data from the new network of storm detection Doppler radars (identified as "NEXRAD" in Figure 2) for ARM data that can be used to evaluate the radar's performance. Several radars are currently installed and others will be installed in 1993. The Oklahoma Climate Survey is installing a network of surface meteorological stations across Oklahoma. Data from this network will be acquired and merged into the ARM data stream, supplementing data from the ARM Extended Facilities.

The first instrument system installed at the Central Facility, a meteorological measurement station with data transmitted through a satellite link, began operation in May 1992. The first data acquired directly by the site data system was from a CLASS-type balloon sonde launched from the Central Facility on May 27, 1992. Through the summer months, additional instrumentation and facilities were installed at the Central Facility; two extended facilities were partially instrumented.

By the end of FY 1992, seven mobile shelters (trailers) were in place at the Central Facility, shown schematically in Figure 3. These shelters house instruments, the data system, instrument assembly and staging areas, calibration facilities, and the site control center. Utilities including sanitation, power, water, and communications are installed and in operation. Prepared sites for additional instrumentation were completed, and pads for Instrument Development Program instrument evaluations will be finished in FY 1993.

By the end of the fiscal year, the following instruments were in place at the Central Facility:

- meteorological observing station
- CLASS-type balloon sounding system
- microwave water radiometer
- rotating shadowband radiometer
- broadband radiation sensors for downwelling radiation (pyranometer, pyrgeometer, and pyrheliometer)
- energy balance Bowen ratio surface flux observing station
- 915-MHz wind profiler with radio acoustic sounding system.

Meteorological stations and surface flux stations were installed at two extended facilities. The 60-m tower is expected to be installed early in FY 1993, and the 50-MHz wind profiler radar/RASS is expected to be in operation about midyear.

In mid-July, the first data set was transmitted to a Science Team member for evaluation and comparison; it was composed of measurements simultaneously taken from the balloon sounding system and the microwave water radiometer. The Science Team member evaluated the data, which helped identify and correct several problems involving instrument software and data ingest.

Science Team Experiment Support

The ARM program is focused on improving the treatment of radiative energy in GCMs and, therefore, on the physical processes that impact radiative transport in the atmosphere. The scientific

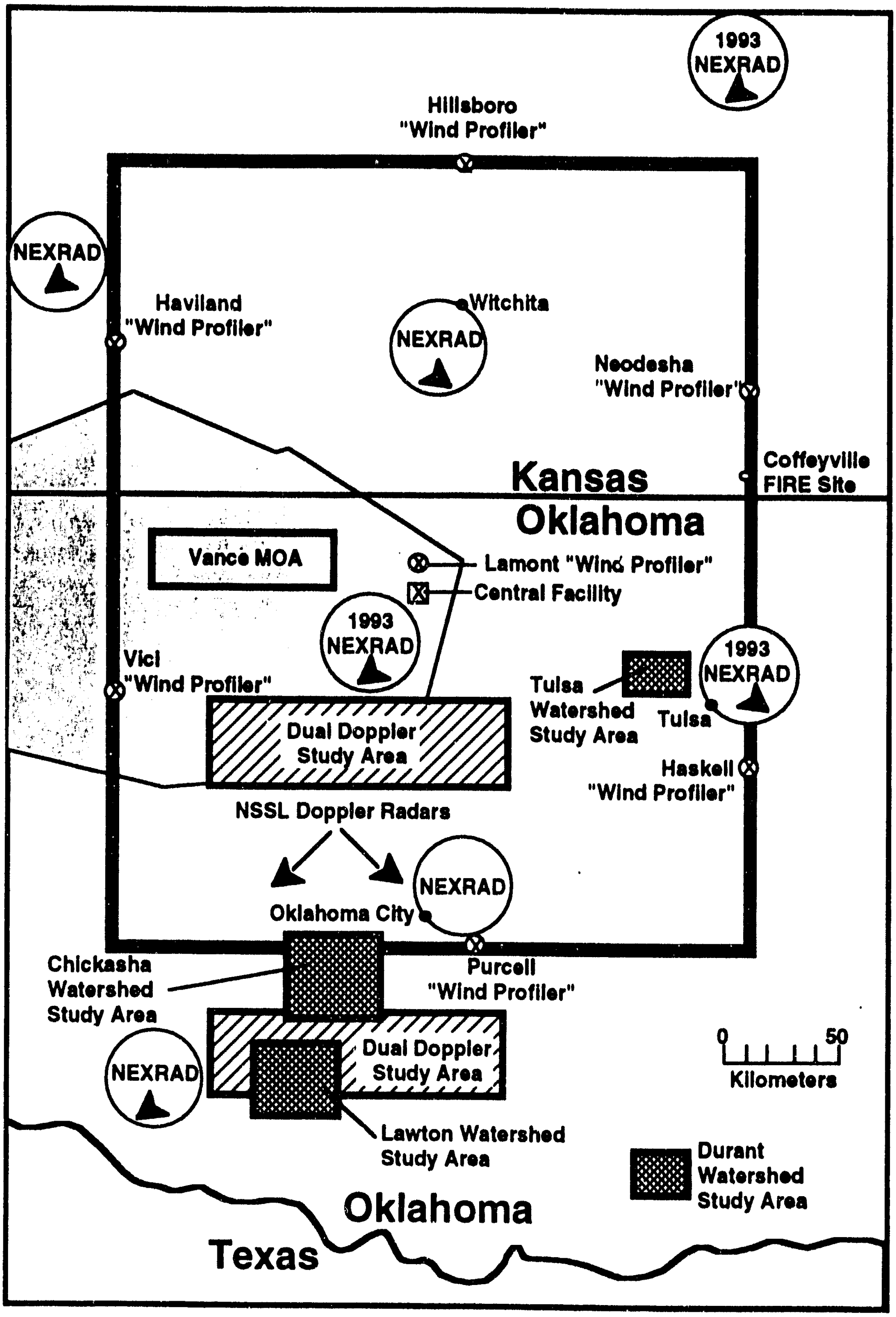

FIGURE 2. Southern Great Plains CART Site and External Data Sources.

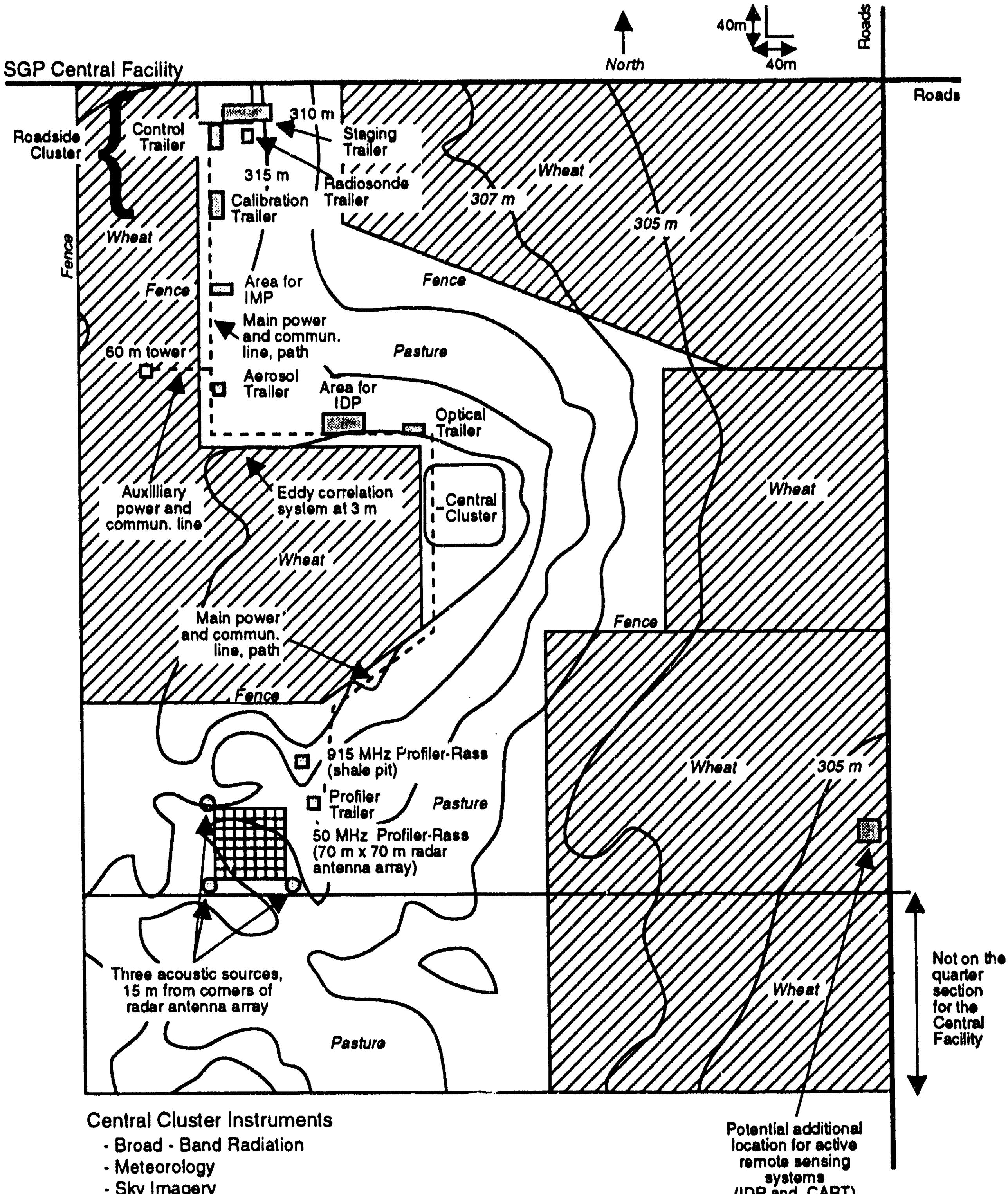

FIGURE 3. Schematic of Central Facility for Southern Great Plains CART Site.

issues facing the ARM Program can be stated in the context of three broad topics:

- radiative energy transport
- cloud formation, maintenance, and dissipation
- the resolution limits important to representing atmospheric processes in GCMs and related models.

Within these broad contexts, research generally falls into one of three related topical areas:

- validation of models of the instantaneous radiative flux under clear sky, broken clouds, and overcast conditions
- use of measurements to evaluate process models and parameterizations embodied in GCMs
- use of data fusion techniques and four-dimensional data assimilation to address the variability of atmospheric conditions on a scale comparable to a GCM computational grid cell.

To identify the diverse measurement requirements necessary to carry out research in these areas, individual Science Team project teams are participating in the development of Experiment Design documents. These documents describe the objectives, methodology, and prioritized measurements needed to pursue each experiment. About 60% of the Experiment Design documents are in draft or final form.

Experiment Designs define the requirements that drive CART observational strategies and instrumentation; specifically, the field observations and algorithms needed to process the observations. Many algorithms are being developed for implementation at the ARM Experiment Center, but some of the algorithms come from Science Team members themselves and are likewise implemented, for example:

- the atmospheric optical depth at six specific wavelengths using the shadowband radiometer
- the vertical distribution of water vapor using the microwave radiometer.

To ensure that data sent to the Science Team are of known quality, data quality assessment algorithms and models are being implemented. These include, for example, instrument performance models to monitor the microwave radiometer and to compare microwave radiometer data with data from the balloon-borne sounding system. These algorithms were made available by Science Team members.

The data delivered to Science Team members is based on their specific requirements, as described in an Experiment Operations Plan. This plan is derived from the Experiment Design and refined through discussions with individual Science Team members. In effect, these represent an agreement between the Science Team member and the Experiment Center as to the exact specifications for the measurements that the Science Team member will receive. These plans include the delivery mechanism, data format, and electronic addressing necessary to provide the data in near real-time.

Data Management System Development

Following concepts developed in previous years, the design for the data system encompasses three components: the Site Data System, the Experiment Center, and the Data Archive. The Site Data System communicates and controls site instrumentation, ingests data, checks data quality and calibration, and transmits data to the centralized Experiment Center. The Experiment Center receives site data, acquires data external to the ARM program, conducts additional quality checks on the data by intercomparisons, merges and repackages the data into individual data sets, and transmits data packages to individual members of the Science Team. The Data Archive receives data both from the Site Data System and the Experiment Center and serves as the long-term data repository, the data source for retrospective research, and the interface to the external scientific community desiring access to ARM data. The Archive will facilitate the availability of ARM data to the broader climate research community, and to other programs for research that extends well beyond climate and global change issues.

The software systems of both the Site Data System and the Experiment Center are based on the National Center for Atmospheric Research (NCAR) Zeb[a] software and are being developed by the ARM Program to ingest, process, display, and store sizable quantities of data in near real-time. The hardware at both the site and the Experiment Center is largely based on Sun work stations; the Experiment Center incorporates a Convex system for more demanding processing that includes line-by-line propagation model development and execution.

The Site Data System was implemented with a dual capability. A "Production System" is the primary system for acquiring data from operational instruments, the site log, and other site data sources, and passing that data to the Experiment Center and the Archive. The "Development System" develops and evaluates new software off-line, including the development of interfaces and ingest modules for new instruments. Once confirmed, new software is incorporated into the production system for routine use. The production system is largely complete, but some problems and inconsistencies remain to be resolved early in FY 1993.

The Experiment Center is also operational, but requires development of additional software components; significant components include the ingest modules for accessing available external data. In FY 1992, the capability to ingest most surface weather data was completed, including National Weather Service sounding data and imagery from geostationary and polar orbiting satellites. Ingest modules for gridded fields of atmospheric data, radar data, and satellite sounding data will be prepared in the near future.

The Experiment Center depends on the Experiment Operations Plans for the procedures to support the recipients of data packages, who include all members of the Science Team and project personnel involved in developing new data processing techniques or analysis tools and products. About 30% of the Experiment Operations Plans are completed in draft or final form.

The Data Archive was established on an interim basis, pending the acquisition of a computer system adequate for handling many data streams and users simultaneously. Until that new capability is developed, the Data Archive will acquire and hold ARM data, but have limited capability to retrieve and disseminate data.

Collaborative Pilot Studies

Limited pilot studies have been valuable in evaluating the performance of instruments and confirming site operations concepts. Several pilot studies were conducted during the past year and one is continuing into FY 1993.

From November 13 through December 17, 1991, the Spectral Radiance Experiment (SPECTRE) was conducted at Coffeyville, Kansas, in conjunction with the First International Satellite Cloud Climatology Project Regional Experiment dealing with cirrus clouds (FIRE-CIRRUS). The data acquisition objectives in this experiment were similar to those planned at the Southern Great Plains CART site to document the instantaneous radiative flux. The major SPECTRE objective was to obtain accurate measurements of the downward spectral long-wave radiance under clear sky and cirrus cloud cover conditions, and the vertical distribution of temperature and moisture. A range of highly desirable conditions was captured, including cold-dry, cold-wet, warm-dry, and warm-wet weather conditions. Because one of the key objectives of the experiment was the almost immediate examination and comparison of data, real-time data acquisition, and quality control were important. The experiment was a testing ground for candidate concepts and procedures to be implemented in CART site data systems.

In June 1992, ARM Science Team members and collaborators returned to the Boardman, Oregon area to study the effects of heterogeneous distributions of surface heat and water vapor fluxes on boundary layer properties. The area is characterized by the contrast of semi-arid steppe bordered by irrigated farmland. Lessons learned the previous year were successfully applied, and procedures were improved to develop more complete

(a) Zeb is a software system developed by the National Center for Atmospheric Research to support field atmospheric research programs. Zeb is the basis for the implementation of the Site and Experimental Center data systems. Its modular architecture for ingesting and processing data makes the system expandable to handle virtually any instrument system or data type, to the limits of the host computer system.

descriptions of conditions for the principal crop areas, to document wind over the steppe and neighboring fields, to document more extensively differences in latent and sensible heat fluxes over the differing land surfaces, and to investigate the impact of the surface features on the structure of the planetary boundary layer. This was largely a DOE effort, but included collaborations with several NOAA laboratories. The results of these campaigns will guide similar efforts and research at the Southern Great Plains site.

Also in June 1992, the ARM Program collaborated in supporting the use of several instruments in the FIRE - Altostratus Transition Experiment (ASTEX) in the Azores. A collaborative effort between DOE and NOAA was part of an extensive international program involving Great Britain, France, Germany, and Russia, among others. In parallel, DOE supported an effort to evaluate the use of a small catamaran buoy for obtaining flux measurements over the open ocean. The knowledge gained from ASTEX, and the experience of operating in the subtropical ocean environment will assist the ARM Program in planning the CART measurement strategies for several ocean locales.

Planning and preparation continued for the Pilot Radiation and Observation Experiment (PROBE) to be conducted as part of the Tropical Ocean - Global Atmosphere (TOGA) field program in the tropical western Pacific Ocean from November 1992 through February 1993. The Site Program Manager and Site Scientist for the Tropical Western Pacific Ocean CART site are leading PROBE. PROBE will provide the opportunity to gain experience in conducting operations in a remote area, and in using and maintaining highly sophisticated instruments in a tropical ocean environment. A seagoing shipping container ("sea-tainer") was equipped to support this field program and to shelter some equipment and instrumentation. The experience in creating modularized site components will be a guide for developing the CART site in this region and possibly in other locales. PROBE is a collaboration between DOE, NOAA, NCAR, and the National Aeronautics and Space Administration (NASA).

External Program Coordination

The ARM program is one of several major research programs that addresses aspects of climate change. It complements related research programs that are focused on new observational capabilities and a new generation of predictive climate models.

Complementary programs in the vicinity of the first operational ARM field site in the southern Great Plains include

- The National Weather Service Modernization Program
- The National Weather Research Program (commonly known as STORM)
- The Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP)
- The GEWEX Global Water Vapor Program (GVAP)
- Winter Icing and Storms Project (WISP)
- The Oklahoma Mesonet.

The modernization program of the National Weather Service and the development of the Oklahoma Mesonet will directly benefit the ARM program. About 35 automated weather reporting stations in the Mesonet are within the boundaries of the ARM site; data from these sites will be acquired routinely and made part of the ARM data base.

The GEWEX and STORM programs continue to be closely coupled with the objectives of the ARM Program. The GEWEX Continental-Scale International Program will be located near the Southern Great Plains site, and close collaboration will ensure maximum benefit to both efforts. To ensure data system compatibility with both programs, common software and compatible software protocols are being used.

Future Research

Phased implementation of the Southern Great Plains site will continue into FY 1993, with anticipation that the site will be fully operational toward the end of the fiscal year. Efforts to complete the installation of the Central Facility will continue through December 1992; these efforts will then gradually shift to the boundary and extended facilities. It is anticipated that several auxiliary sites will be developed as soon as the digital imagery capability is developed.

The data system will be largely in place and operating early in FY 1993, but Experiment Operations Plans must be completed. The development of these plans partly depends on the Science Team members; however, the plans are anticipated to be largely complete in the second quarter of the fiscal year. Some software development to complete the transition of Zeb to ARM Program needs will be required well into the fiscal year, but the data system will be operational.

Assessments of the basic scientific questions facing each locale will continue, with analysis reports for the Southern Great Plains and the Tropical Western Pacific sites expected early in FY 1993. Recommended options for strategies for deployment to the tropical western Pacific will be completed and presented for consideration. A siting strategy will be selected and the initial instrumentation procured and modularized for easy deployment and integration into the operational system.

The intense period of taking measurements in the PROBE campaign, January-February 1993, will be followed by data analysis and application of lessons learned to ARM Program needs. PROBE data will be available through the CART data system some time after March 1993.

Interagency and interprogram coordination remain central features of the ARM Program. The involvement of NOAA is substantial; the NOAA Forecast Systems Laboratory will be the site operator for the Southern Great Plains site through CY 1993. NCAR is involved in instrument and model development, with a particular focus on vertical profile specification and improvement of the Zeb software system. The ARM field efforts will continue to be coordinated with the STORM and GEWEX/GCIP programs. Other agencies with which ARM Program operations and plans will be coordinated include NASA, the National Science Foundation, and the Department of Defense.

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Characterization of Cloud/Aerosol Interactions with Solar and Long-wave Radiation

N. S. Laulainen, J. J. Michalsky,[a] *L. C. Harrison,*[a] *N. R. Larson, and J. L. Berndt*

The purpose of the Quantitative Links component of the U.S. Department of Energy's Expanded Carbon Dioxide Research Program is to quantify linkages between changes in atmospheric composition and the temperature of the planet. While significant efforts have been made to understand expected changes in climate that may result from an increase in CO_2 and other greenhouse gases, there has also been a growing recognition of the role that clouds and aerosols have in the regulation of 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, greatly reflect solar radiation, and moderate 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-wave and short-wave radiation to regulate the heating of the planet. To understand how cloud- and aerosol-induced radiative effects vary in time,

(a) State University of New York at Albany.

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 multi-filter rotating shadowband radiometer (MFRSR) to measure direct normal, diffuse horizontal, and global horizontal irradiance in six narrow-wavelength passbands. An additional measurement in a broad passband covering a large portion of the short-wave spectrum approximates total short-wave irradiance. Measurements of down-welling long-wave radiation are made with a pyrgeometer or precision infrared radiometer (PIR). 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 experiment 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 the third year of a five-year research period.

Specific objectives accomplished during FY 1992 were 1) the acquisition of additional support instrumentation; 2) the fabrication, testing, and calibration of the MFRSRs, including additional backup MFRSRs; 3) the operation and maintenance of the field sites, including the diagnosis and correction of malfunctions; 4) data collection and archival; 5) the development and application of data analysis techniques to interpret the measurements; and 6) the 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, developed jointly at PNL and SUNY-Albany. It was described in detail in the previous annual report (Laulainen et al. 1992) and only the essential features are presented here. The MFRSR measures total horizontal and diffuse horizontal irradiance in six narrow-wavelength passbands (nominally defined at 415, 500, 610, 665, 862, and 940 nm) and in one broad band that covers the spectral sensitivity of a silicon photocell and is used to measure total short-wave irradiance. Direct normal irradiance is calculated for these passbands by subtracting the two measurements and dividing by the cosine of the solar-zenith angle. Other measurements made include precipitation, relative humidity, outside air temperature, output from the PIR (including the thermopile output and the temperatures of the PIR dome and case, used to correct the thermopile measurement), upwelling short-wave irradiance, detector temperature, battery voltage, and reference voltage for the thermistors that are used in the PIR temperature determinations. A microprocessor on the main circuit board controls the band motion, acquires data from the MFRSR and auxiliary instruments, and communicates with the outside world via a modem. Data acquisition, processing, and analysis are performed on Sun SparcStation IPC systems and graphics terminals that are available at both PNL and SUNY-Albany.

Calibrations and Tests

An important criterion for proper MFRSR operation is that the receiving optics have a cosine response, i.e., the response decreases as the cosine of the angle of incidence. The cosine test facility, constructed at ASRC, was used to establish response curves for each MFRSR unit. With this response information, the direct normal irradiance component can be corrected. The diffuse contribution at high angles of incidence, while unknown (because the spatial or angular distribution of diffuse radiance is generally not known), is very low because it is also weighted approximately by the cosine of the solar-zenith angle. Therefore, the error made in global and diffuse horizontal irradiance measurements is generally small, even without correction.

The accuracy of the cosine correction algorithm was investigated by comparing Langley plots (plots of the natural logarithm of the direct normal intensity versus air-mass path length) and aerosol optical depths determined from observations of direct normal irradiance obtained from the Mobile Automated Scanning Photometer (MASP) developed by Kleckner et al. (1981), and that computed from the MFRSR irradiance measurements. The results of this comparison for data collected during 1991 are displayed in Figure 1. Although the wavelength bands for the MASP and MFRSR units were not the same, the plot shows that the interpolated aerosol optical depths were within 0.01. This result indicates that the cosine correction algorithm applied to the MFRSR data appears to reproduce direct beam irradiance measurements.

To establish calibration values for the MFRSRs, the filter/detectors were characterized with an optical radiation calibrator. Changes in instrument calibration that may have occurred during the past year were traced via the Langley technique for all clear days. Precipitation was calibrated using a water bottle with a known flow rate. Ambient temperature and humidity were calibrated against a laboratory calibrated temperature and humidity probe. The albedo sensor and the silicon detector were calibrated against a standard precision pyranometer. The PIRs were not recalibrated because of some still-unresolved disagreements between the calibrations of the two PIRs at the ASRC site.

Site Operation and Maintenance

The installation of instruments at the nine sites of the Quantitative Links Network (QLN) was completed in the fall of 1991. Site selection was based on the availability of electric power and telephone service, the existence of ongoing research or monitoring activities, and "regional representativeness," i.e., no influence by local sources of air pollution. The nine sites selected for the QLN are shown in Figure 2. They are:

- Albany, New York--the "home-base" site at ASRC, where hands-on troubleshooting of operational problems in the field units can be carried out
- Ithaca, New York--currently a National Dry Deposition Network (NDDN) operated by Cornell University
- Howland, Maine--a remote NOAA Dry Deposition Research Network (NOAA-DDRN) site operated by the University of Maine

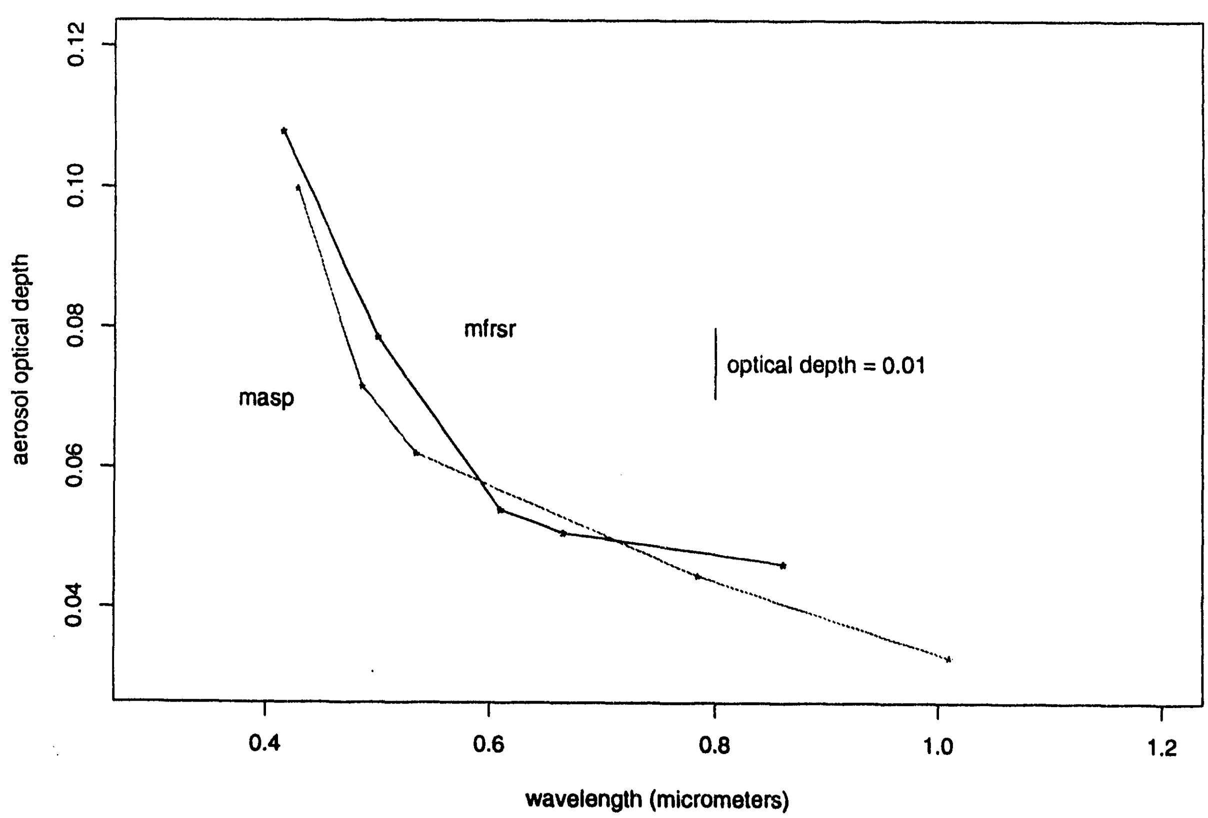

FIGURE 1. Comparison of Aerosol Optical Depths Derived from MASP and MFRSR Observations Taken in 1991.

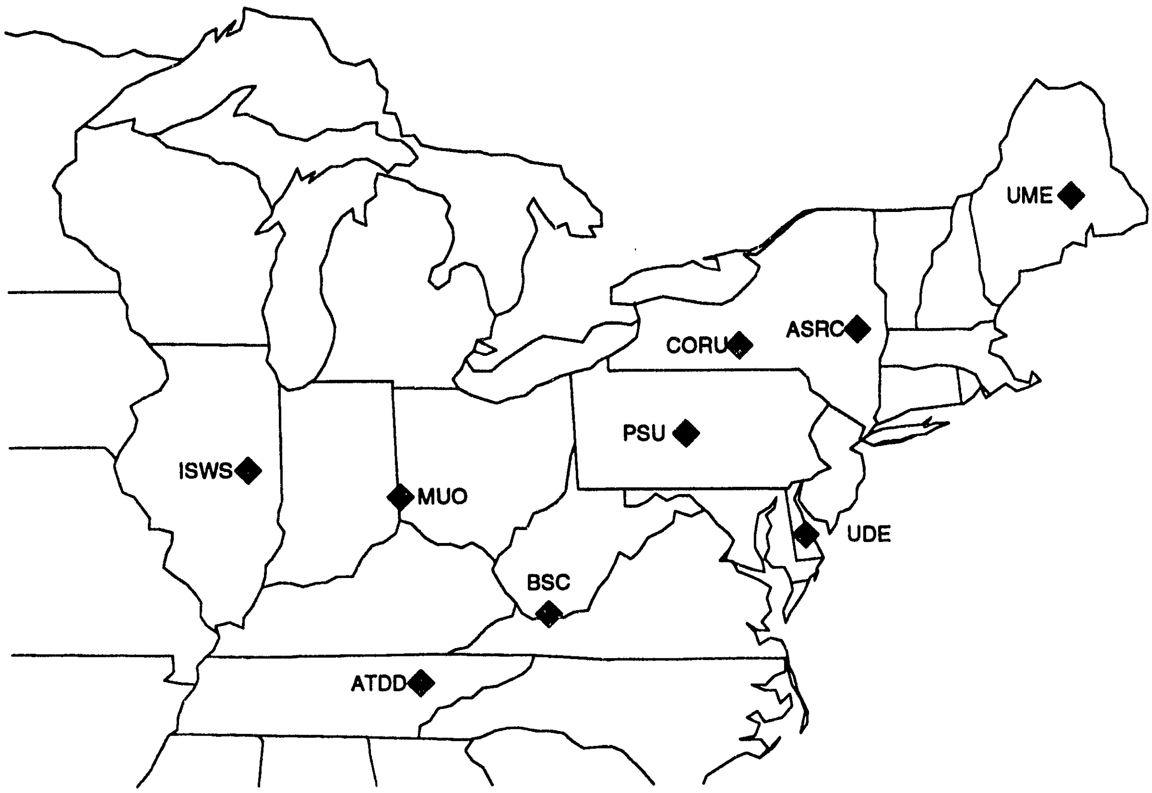

FIGURE 2. Location of the Quantitative Links Network Sites.

- Pine Grove Mills, Pennsylvania--an ARM Science Team site, in proximity to a NOAA-DDRN site, operated by Pennsylvania State University
- Oak Ridge, Tennessee--a NOAA-DDRN site operated by the NOAA Atmospheric Turbulence and Diffusion Division
- Bluefield, West Virginia--a site with a well-maintained solar radiation record operated by Bluefield State College
- Bondville, Illinois--a NOAA-DDRN site operated by the Illinois State Water Survey
- Oxford, Ohio--a NDDN site, with a 10-year solar resource data history, operated by Miami University of Ohio
- Lewes, Delaware--a coastal site operated by the University of Delaware's College of Marine Studies.

Site attendants clean the optical surfaces and check sensor operation on a weekly or more frequent basis. Occasionally, they perform troubleshooting tasks under the careful supervision of project managers. Normally, each site is visited annually for maintenance and instrument calibration. The principal research program at the Maine site (NOAA-DDRN) was discontinued in the fall of 1992; however, the QLN component will continue.

During FY 1992, six site visits were made to correct malfunctions. Most of these were associated with the modems. A procedure has been developed enabling the original modems to be reset instead of replaced. In some cases, the site attendant is allowed to fix or replace defective parts; for example, when static discharges have rendered some integrated circuits useless and the parts can be clearly identified by telephone or other remote communication.

Another malfunction was related to changes in ambient temperature. Under normal, low wind speed conditions, an internal heater maintains the MFRSR detector head at 40°C. Maintaining the detector head at a constant temperature is desirable to minimize temperature-dependent instrument response drifts. However, in cold and windy conditions the detector head temperature dropped to as low as 15°C below the prescribed steady-state temperature. For this reason, each head and circuit board was shipped back to ASRC and the head was remachined, allowing additional insulation to be placed between the detector cavity and the external housing. Before and after this remachining, the filter/detectors were calibrated with the optical radiation calibrator.

Data Management

The goals of the data management task are to acquire a complete and reliable atmospheric radiation data set, and to provide it to principal investigators and the scientific community in an easy-to-use format. PNL is responsible for primary data collection and management. The QLN generates approximately 90,000 bytes of solar and atmospheric radiation and meteorological data each day. The data are transferred almost daily by each of nine QLN stations to a host computer at PNL. Data management software interprets the data files and converts all of 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. In the event that the PNL computer goes off-line, a redundant system at ASRC retrieves the data.

The performance of each network station is assessed on a weekly basis by converting the data to physical units and plotting it. If any station or its sensors malfunctions, the appropriate site attendant is notified and given specific instructions on how to return the station to normal operating condition. If necessary, a visit by a technician from ASRC can be arranged.

During FY 1992, data were acquired from the network with a success rate of 89% for all stations combined. The success rate for individual units ranged from 76% to 97% of the possible number of days to obtain data. Data loss resulted mainly from downtime to reinsulate and calibrate the MFRSRs, although some stations occasionally experienced modem problems that prevented the transmission of data. All of the data processing software was completed, and development efforts shifted to analysis software. An algorithm to perform the Langley method of atmospheric optical depth determination, including corrections for the cosine response of the MFRSRs, was implemented.

The processed data files become the master data files to be used by the project and other Atmospheric Radiation Measurement (ARM) Science Team investigators. The master data files are available for on-line use by onsite (PNL) investigators. Offsite investigators can access the master data files through requests to the data system manager and can receive copies via magnetic storage tapes, discs, or electronic mail.

Data Analysis and Interpretation

Much research associated with change in radiation climatology will occur only when the data base contains a sufficiently long time series. Some possible research approaches are discussed in the next section. At present, development and application of analysis software are under way in anticipation of this larger data base. A significant component of the research is the characterization of the radiative properties of atmospheric aerosols. Earlier, when a single one-channel rotating shadowband radiometer was used, it was possible to interactively reduce data from individual days. With nine MFRSRs in the QLN, each containing six narrow passband filters, and up to 27 MFRSRs expected to be in operation at the Southern Great Plains ARM/CART Site, it is imperative to have an automated reduction procedure. At ASRC, an automated method to reduce a complete set of data has been compared to a more subjective method. For periods when the data overlap, the output of the two methods correlates very well.

Because using the MFRSR calculation of direct normal irradiance is an unconventional method of performing sunphotometry (i.e., by subtraction of diffuse horizontal from total horizontal irradiance), it must be demonstrated how the optical depths obtained compare with the standard direct measurement of solar intensity. A preliminary study was performed by comparing the optical depths derived from the MASP and MFRSR, as previously described. A direct comparison can also be made by obtaining simultaneous measurements with the standard MFRSR and a direct MFRSR module mounted on an automated solar tracker. The direct module is created by fitting a MFRSR head into a Gershun tube that blocks all but the direct irradiance. This comparison test was started in late FY 1992. Preliminary comparisons indicate close agreement between the two measurement methods. Some small biases (optical depth values of 0.001-0.003) that could arise from differences in effective fields of view of each instrument, or from mismatches in filter transmission properties, cannot yet be ruled out. Because this preliminary analysis includes only ten data points, a more definitive analysis will be possible when more data are acquired.

The Mt. Pinatubo eruption in June 1991 has significantly perturbed the stratosphere, introducing an estimated 20 million metric tons of SO_2. The SO_2 has been subsequently converted to sulfuric acid and mixed with water to produce aerosol particles that are about 75% H_2SO_4 by weight. Because the aerosol particles are small and effectively decoupled from efficient removal processes that occur in the troposphere, this aerosol is only slowly removed over a number of yeas. In earlier studies (Pearson et al. 1988; Michalsky et al. 1990), aerosol optical depth data acquired during clean stratospheric conditions were used to establish the seasonal variability of the tropospheric aerosol burden. The net effect of the El Chichon eruption was established by subtracting the tropospheric background. The QLN was established about six months after Mt. Pinatubo erupted, but just before it reached peak light extinction. A time series of residual aerosol optical depth showing the effects of volcanic perturbations, including those from the El Chichon and Mt. Pinatubo eruptions until the present, are shown in Figure 3. These data were derived from MASP observations at the Rattlesnake Mountain Observatory in Richland, Washington. By continuing QLN observations for several years, it will be possible to establish the background tropospheric aerosol burden and clearly define the net effect that the Mt. Pinatubo eruption had over the nine sites.

Two papers were presented at conferences this year. A paper on the cosine bench that tests the cosine response of instruments that measure total horizontal irradiance or illuminance was presented at the 1992 American Solar Energy Society (Michalsky et al. 1992). The paper described the cosine bench instrument and presented some results of tests on the cosine responses of commercial pyranometers and photometers. The cosine bench instrument is crucial to the operation of the shadowband instrument because the direct normal irradiance is calculated from the measurement of total and diffuse horizontal fluxes.

Another paper was presented at the 1992 American Geophysical Union's Spring Meeting in May at Montreal, Canada (Larson et al. 1992). This paper describes early results from measurements of the volcanic perturbation of Mt. Pinatubo. It is based partially on a single-channel version of the MFRSR and leads into the research on volcanic perturbations that will be more completely described when the MFRSR data base includes volcanically unperturbed background data. Preliminary results indicate that the peak Mt. Pinatubo aerosol perturbation exceeds the El Chichon perturbation by about 50%. This is consistent with other measurements and the fact that Mt. Pinatubo released 20 million metric tons of SO_2 compared to El Chichon's 6 million metric tons of SO_2. The Mt. Pinatubo SO_2 was more evenly distributed between the northern and southern hemispheres, while the El Chichon SO_2 was confined to the northern hemisphere.

Future Work

Although some effort will be required to maintain and recalibrate the field units, the effort in FY 1993 will focus on the development and application of data analysis software. Analysis of data with respect to the Mt. Pinatubo eruption will continue. Other significant activities will include:

- the purchase of a 1.6 gigabyte disk for use at ASRC to allow for additional storage space for both the data base and for the products that result from the analyses

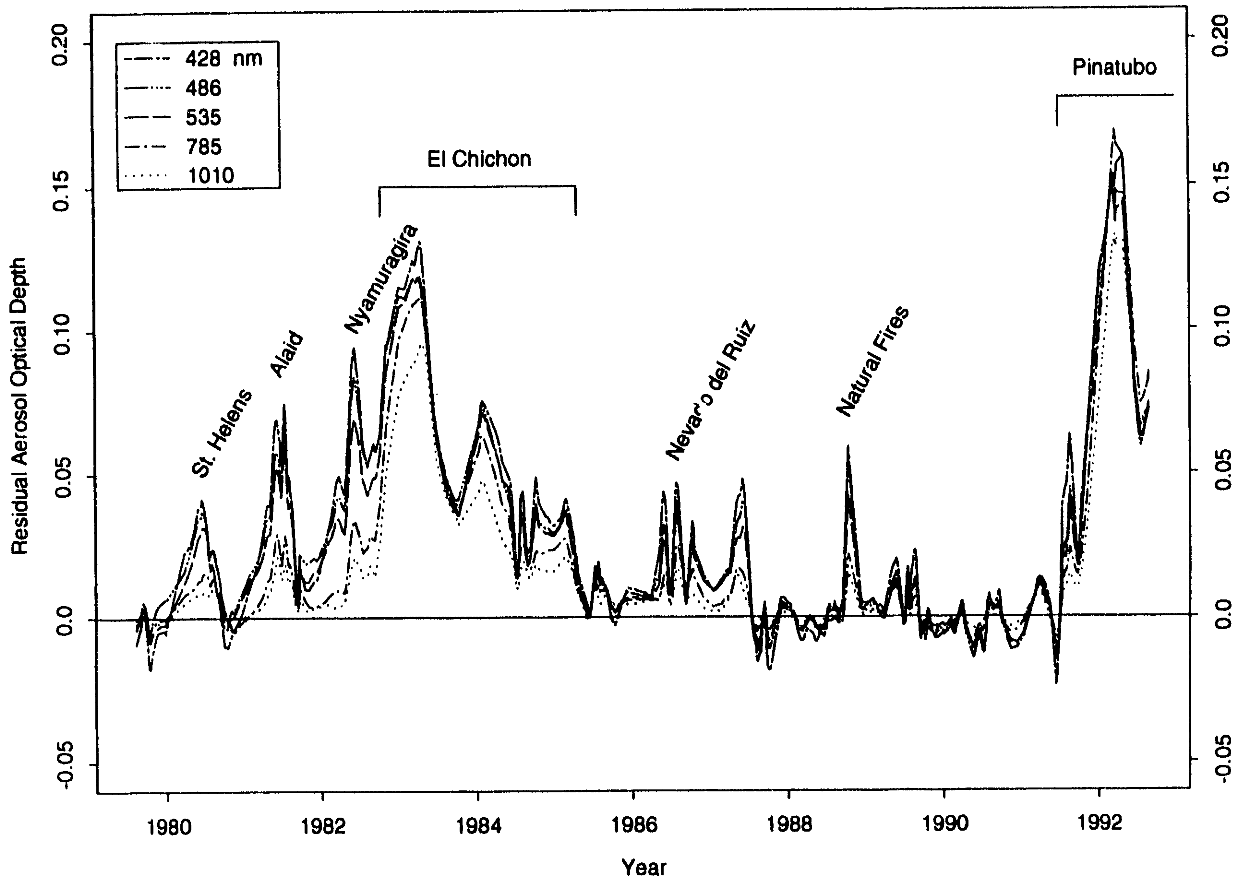

FIGURE 3. The Effect of Volcanic Perturbations on Aerosol Optical Depth at Several Wavelengths as Determined from MASP Observations.

- the calibration of all radiation sensor units in the summer and fall of 1993, including the PiRs, assuming that the recalibration problems experienced this year are resolved; emergency maintenance will be performed as needed, with an emphasis on solving problems with the aid of the site attendants
- the reduction of clear day data using the automated data reduction technique being developed at ASRC; additional algorithms will be obtained or developed to extract from these data aerosol size distributions, water vapor, and ozone total column
- the development 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
- the investigation of optical depths for opaque cloud cover; detection of opaque clouds by nulling the direct beam component; accumulation of statistics on their frequency and thicknesses as measured by the diffuse irradiance component
- the search for correlations between the measured parameters and the downwelling shortwave and long-wave irradiances; as they become available, observed surface radiative fluxes will also be correlated with satellite-derived top-of-atmosphere long- and shortwave fluxes
- the obtaining or developing of numerical analysis packages that will allow the nature of the variability in the measured and derived parameters of radiation to be established; an example is the cumulative frequency distribution (CFD). Categories of total short-wave

irradiance could be established, up to the maximum level detected, with a CFD plot showing the fraction of the total sample that belongs to a value less than a selected irradiance level. Data for a cloudy month will result in a CFD that is shifted to the lower categories, and vice versa for a clear month. Comparisons can be made for the same month or season of the year to establish variability and to test for variations beyond those expected.

- the submission of a paper on the cosine bench facility and the results of testing of several commercial instruments to *Solar Energy*
- the submission of a paper on the effects of the Mt. Pinatubo eruption to *Geophysical Research Letters*
- the submission of a paper on the automated aerosol optical depth reduction technique to the *Journal of Atmospheric and Oceanic Technology*
- the presentation of a poster on the MFRSR instrument at the American Meteorological Society Meeting in January 1993
- the presentation of papers at the Optical Remote Sensing of the Atmosphere conference in Salt Lake City in March 1993 on further effects resulting from the Mt. Pinatubo eruption.

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A Stratiform Cloud Parameterization for General Circulation Models

S. J. Ghan, L. R. Leung, R. C. Easter, J. E. Penner,[a] *and C. C. Chuang*[a]

The crude treatment of clouds in General Circulation Models (GCMs) is widely recognized as a major limitation in applying these models to predictions of global climate change. The purpose of this project is to develop a parameterization for stratiform clouds in GCMs in terms of bulk microphysical properties and their subgrid variability. Precipitating cloud species will be distinguished from nonprecipitating species, and the liquid phase will be distinguished from the ice phase. The size of the nonprecipitating cloud species (which influences both the cloud radiative properties and the conversion of nonprecipitating cloud species to precipitating species) will be determined by predicting both the mass and number of each species. Figure 1 summarizes the various cloud variables and their interactions. The Atmospheric Radiation

(a) Lawrence Livermore National Laboratory, Livermore, California.

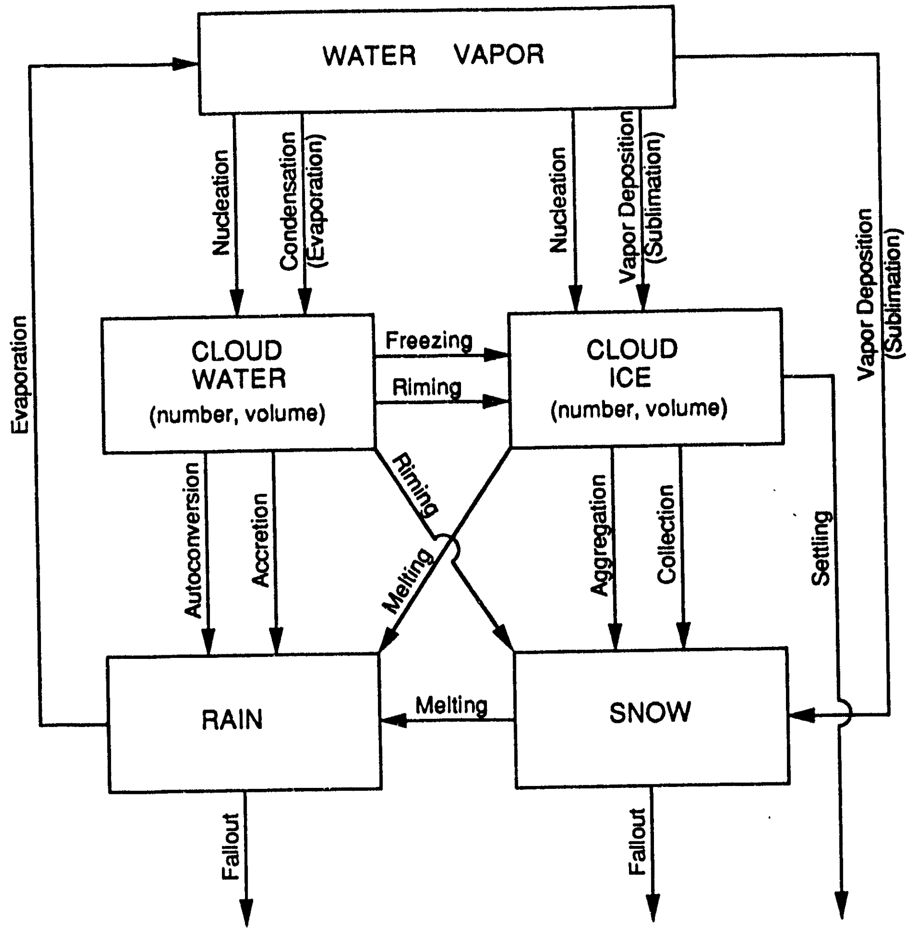

FIGURE 1. Cloud Variables and Microphysical Processes Represented in the Stratiform Cloud Parameterization.

Measurement (ARM) Clouds and Radiation Testbed (CART) facility will be used to verify the parameterization of clouds and their radiative impact in GCMs.

The FY 1992 project goals were to

- adapt an existing cloud microphysics parameterization for application to a GCM
- introduce cloud droplet number as a predicted variable
- initiate work on representing subgrid-scale cloud variability
- construct a one-dimensional column cloud model for application to ARM CART facilities.

Cloud Microphysics

Two journal articles relating to cloud microphysics were prepared during FY 1992. The first article (Ghan and Easter 1992) introduced two approximations that together permitted a tenfold increase in the permissible time step of a bulk cloud microphysics parameterization that was originally developed for mesoscale cloud models (Cotton et al. 1986). This increase in efficiency permits the bulk parameterization to be applied to stratiform clouds in a GCM without greatly increasing the computational demands of the model. The parameterization has now been applied to the PNL version of the National Center for Atmospheric Research (NCAR)

Community Climate Model (CCM) and appears to yield satisfactory cloud and radiation fields.

The second journal article (Ghan et al. 1992) resulted from efforts to introduce cloud droplet number as a predicted rather than prescribed variable in the cloud microphysics parameterization. We developed a parameterization of droplet nucleation that simply and accurately expresses the number of cloud droplets formed in a rising air parcel in terms of the total aerosol number concentration and the vertical velocity. The expression is derived from several approximations to the classic Köhler nucleation theory.

Subgrid Cloud Parameterization

Subgrid-scale variations in cloud microphysical processes must be accounted for in GCMs because cloud processes are highly nonlinear and poorly resolved by the coarse grid size of GCMs. During FY 1992, we initiated the development of a statistical formalism that expresses subgrid-scale variations in cloud microphysical properties in terms of idealized probability distributions. Joint probability distributions were introduced to account for the dependence of many cloud microphysical processes on combinations of cloud variables. A high school mathematics instructor, James McKay from Naches, Washington, spent the summer of 1992 at PNL using the Mathematica software to analytically relate the parameters of joint probability distributions to the statistical moments of the cloud variables.

Column Cloud Model

An essential task in the development of cloud parameterization is its verification. Although some aspects of verification will be achieved using climatological simulations with the PNL version of the NCAR CCM, more control is possible by applying the cloud parameterization to forecast experiments in the field. This project will use the ARM CART facilities to provide boundary conditions to drive a one-dimensional column cloud model, and to provide cloud and radiation observations for model verification. During FY 1992, the column model was constructed and used to develop the cloud microphysics parameterization.

Future Work

The following tasks are planned for FY 1993 and FY 1994:

- to evaluate the cloud parameterization in the GCM with prescribed cloud droplet number and compare simulated cloud, precipitation, and radiation fields with surface and satellite observations
- to apply the droplet number parameterization to the GCM and evaluate for prescribed aerosol distribution; to compare simulated and observed cloud droplet number as well as other cloud-related fields
- to complete the representation of subgrid variations in cloud microphysics and evaluate the impact of subgrid variability on the climatology simulated by the GCM
- to evaluate the cloud parameterization when applied to ARM CART sites in a column model and to consider several verification strategies, such as prescribing rather than predicting the cloud water field.

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Photometric Studies of Clouds from an Atmospheric Radiation Measurement (ARM) Site

C. D. Whiteman, J. M. Alzheimer, G. A. Anderson, and W. J. Shaw

An instrument development project is under way to develop a small tethered-balloon sounding system to collect routine in situ vertical broadband radiometric profiles to heights of ~1500 m above ground level under cloudy and noncloudy conditions. The major technical objective of this project is to construct a stable self-leveling platform that will keep radiometric instruments horizontal, regardless of balloon motion.

The project approach has been to develop a stabilized platform that is carried in a tetherline harness some distance below a small helium-filled balloon. An automatic control loop is used to keep the platform level. The platform will carry sensors to measure the upward and downward-directed streams of long- and short-wave radiation, and additional sensors to measure the platform's attitude, including azimuth and elevation angles. Data are processed and stored onboard using a small lightweight, programmable data acquisition system. The balloon itself will carry a separate meteorological data collection system to collect vertical profiles of basic meteorological data as the balloon ascends.

The project has been organized into three phases. The first phase, initial design and prototyping, has been successfully completed with the demonstration of a prototype stable platform. The second phase is further development of the prototype and completion of the data interfacing. This phase is now nearly complete, and reported on below. The final phase is field testing and strengthening of the design for operational use at Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) sites.

Background

Funding for the project began in FY 1991, during which design specifications were completed and an initial design was selected. A prototype platform was constructed and a mathematical model of a tilted radiometer was constructed to aid in determining design specifications. The stable platform, termed the Sky Platform, carried radiometric sensors and was stabilized by an active control loop. A second platform, termed the Motion Sensing Platform (MSP), was designed to measure the lateral and angular accelerations to which the Sky Platform would be exposed, and to provide the data necessary to close the Sky Platform's control loop. A working prototype Sky Platform was demonstrated at the ARM Science Team Meeting in October 1991 (Whiteman et al. 1992).

Project Goals for FY 1992

Several major tasks were scheduled for FY 1992. A radiometric field experiment was planned to test the mathematical model of a tilted net radiometer, modifications were planned for both the Sky and Motion Sensing Platforms, and flight tests were scheduled to test the performance of the platforms and the level sensors.

FY 1992 Major Accomplishments

A radiometric field experiment was conducted to evaluate the performance of our instrument model, which was developed to specify, on the basis of theory, the tolerances required for keeping the platform level relative to radiometric measurement errors introduced by various tilt angles. In the field experiment, pyranometers, pyrgeometers, and pyrradiometers were tilted at prescribed azimuth and inclination angles over the course of a 24-hour period. These data were compared to data from horizontal instruments to quantify measurement errors due to tilting. A research paper on this topic was completed and accepted for presentation at the Eighth Symposium on Meteorological Observations and Instruments (Shaw and Whiteman 1993).

An improved stabilized platform was constructed using strong and lightweight materials. The Sky Platform control loop was closed using calculations from a mechanical model of platform dynamics. The design of the MSP was also improved. A research paper on the design of the Sky and Motion Sensing Platforms was submitted and accepted for presentation at the Eighth Symposium on Meteorological Observations and Instruments (Alzheimer et al. 1993).

The Sky and Motion Sensing Platforms were significantly modified in FY 1992. The Sky Platform is now somewhat larger (76 cm on each side), is made of graphite instead of aluminum, has a redesigned mount to allow easier interchange of radiometric sensors, and has enclosed pulleys to prevent the harness lines from coming out. A flux gate magnetometer was mounted on the Sky Platform and the platform was modified structurally and electronically to accommodate new radiometric sensors that will become available in FY 1993. These new sensors will allow measurement of all individual broadband radiometric components (incoming and outgoing long- and short-wave radiation), rather than solely net radiation. New 2-axis controllers were built. Linear amplifiers were replaced by switching amplifiers to reduce power consumption. The complete Sky Platform, including batteries, now weighs only 1.5 kg.

The MSP was redesigned to take advantage of a new and improved method of determining angular accelerations. An array of nine miniature solid-state accelerometers collects the raw data from which balloon motions are determined. Figure 1 shows the coordinate system and accelerometer orientation for the newly designed MSP. Accelerometer data from this configuration are used to solve for angular accelerations using equations listed below:

$$\dot{\omega}_x = (a7 - a3)/2r_y - (a9 - a2)/2r_z \quad (1)$$

$$\dot{\omega}_y = (a8 - a1)/2r_z - (a5 - a3)/2r_x \quad (2)$$

$$\dot{\omega}_z = (a4 - a2)/2r_x - (a6 - a1)/2r_y. \quad (3)$$

This system of linear equations is inherently stable. Determining angular accelerations does not require knowing an angular velocity from a previous integration step. The method thus appears advantageous to other methods previously considered for this purpose.

Two single-axis rate sensors were purchased in FY 1992. They will be installed on the MSP and Sky Platforms to measure the accuracy of accelerometer-based tilt measurements and will demonstrate the efficacy of the control-loop-stabilized platform.

A new onboard data acquisition and storage capability has been developed for both the MSP and the Sky Platforms. This small data acquisition system samples data at 100 Hz and stores data onboard on a 1-Mb credit card-size storage medium. A multiplexer allows data to be collected from the extended number of radiometric channels.

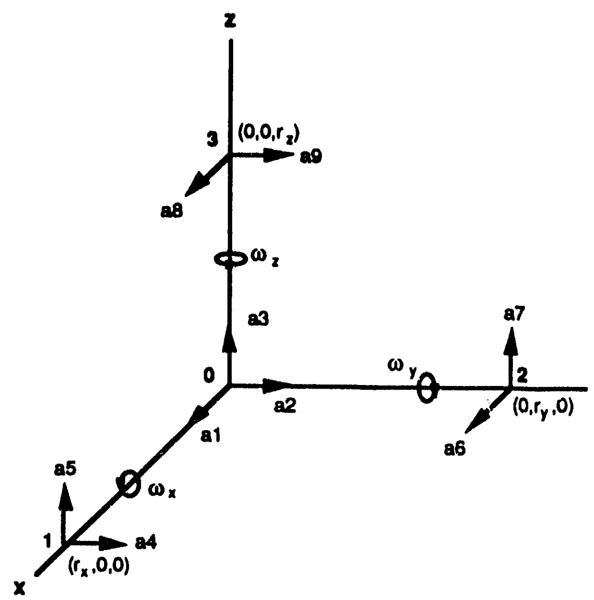

FIGURE 1. Nine Accelerometer Method for Determining Rotational Measurements with Linear Accelerometers. The coordinate system is shown along with the positioning and orientation of the linear accelerometers a1 through a9. Angular velocities are also shown on each of the coordinate axes.

Future Plans

The major effort in FY 1993 will be performing flight tests of the MSP and Sky Platforms. New radiometric sensors will be purchased and installed on the Sky Platform. We will evaluate the performance of three level-sensing methods using the rate sensors as the standard. By year-end, we expect to have completed a full evaluation of the performance of the MSP and Sky Platforms. If capital equipment funds are available as expected, we will purchase a tethered balloon meteorological sounding system to replace the borrowed one that we are now using. Late in FY 1993 or early in FY 1994 we will test radiometric profiles obtained from the Sky Platform against those obtained from an instrumented tower at the ARM Southern Great Plains site or at Erie, Colorado. In FY 1994 we will strengthen all components of the tethered-balloon sounding system so it can be run routinely at the ARM Cloud and Radiation Testbed sites. Operating characteristics and operating limits of the instrument system will be determined to properly interpret the data and to meet safety and operational requirements.

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Second-Generation Model

J. A. Edmonds

The Second-Generation Model (SGM) is a new model designed to produce estimates of global greenhouse gas emissions for multiple regions of the world at five-year time steps that will extend into the future as far as the year 2100. The new greenhouse gas emissions model is being developed in phases. The first phase consists of constructing model Version 0.0, developing the underlying database to support this version, and then using the model.

At the center of the Version 0.0 model is a new, computable, general equilibrium modeling framework. Most of the detail is found in the energy sector of the model. In addition to the energy sector, the new model will include four other highly aggregated sectoral modules (agriculture, other production, households, and government) along with a price preprocessor, a demographic module, a solution algorithm, and an emissions post-processor. The initial prototype has been completed and tested for a single-period, single-region case. The model parameters will be extended and refined over approximately the next one-and-a-half years, resulting in development of a complete full-scale model, Version 1.0. However, increasingly useful output will be available in the interim. The SGM will also form the core of the Integrated Climate Change Analysis Model, which has the overall objective of improved understanding of the relationship between human activities that generate emissions of greenhouse gases and the potential resulting consequences of changes in atmospheric composition and climate.

FY 1992 Accomplishments

Activities in FY 1992 focused on completing Version 0.0, improving model data, and exercising the model.

The Generic Production/Cost Module was modified to include

- energy production from a depletable resource base
- energy production from a renewable resource base
- time delay between initial investment and initial production for an economic activity.

Economic and energy data continues to be collected. Required data sets are being developed with support from a number of international energy experts through PNL's Advanced International Studies Visiting Scholars Program. Energy data sets for the Former Soviet Union, China, and Brazil have been developed and are being augmented progressively.

Several proposed prototypes of user interface designs are being examined to facilitate the model's use by the largest possible group.

A Greenhouse Gas Processor has been developed that calculates emissions of CO_2, CO, N_2O, NO_x, SO_x, and Volatile Organic Compounds (VOCs) based on the economic activities assessed by the model. Estimates of chlorinated fluorocarbons (CFCs) and substitute emissions are not yet included in the model and will likely be provided as a separate sidebar calculation.

As the fiscal year ended, the model was being parameterized with U.S. data and exercised to examine the effects of carbon taxes and other potential energy policy instruments that go beyond the National Energy Strategy.

FY 1993 Activities

Concurrent with the further development of Version 0.0, work will begin on development of SGM Version 1.0. This work will include

- extension of the Agriculture Module from a single product to as many as ten markets—a biome scheme that reflects changes in land productivity will be implemented and modeling of gradations of water availability will be explored
- separation of the Other Products Module into the following sectors: Manufacturing (both materials-intensive and other manufacturing), Transportation, Health and Other Services, and Education
- incorporation of increasingly sophisticated modeling of the labor supply and educational services demand functions; the basic structure of the Households Module will remain the same—the savings supply will be made sensitive to interest rates and the labor supply will be made sensitive to the education and age of the population
- refinement of the decision-making processes in the Government Module, to include infrastructures, tax rates, and regulatory policies
- expansion of the Energy Module to permit a wider range and more flexibility in choices of technologies
- provision of finer-grained summations of greenhouse gas emissions by the Emissions Calculation Module as the individual production sectors become increasingly disaggregated
- exploration of mechanisms for modeling the behavior of nonmarket economies
- investigation of the role of research and development in the rate of technical progress, with a view toward investing research and development in energy-saving and emissions-reduction efforts.

Carbon Dioxide Ocean Research

J. P. Downing, E. D. Skyllingstad, D. W. Denbo, W. E. Asher, L. F. Hibler, C. R. Sherwood, K. D. Hargrove, and B. DeRoos

The objective of the CO_2 Ocean Research project is to improve understanding of the role of the ocean in CO_2-induced climate change. Staff at both the Pacific Northwest Laboratory and the Battelle/Marine Sciences Laboratory provide technical support to the U.S. Department of Energy's Environmental Sciences Division (ESD) and conduct research into the exchange of CO_2 at the air-sea interface; deep water formation (in ocean general circulation models); and surface-layer processes including air-sea exchanges of mass, heat, and momentum. Direct support to ESD includes developing aqueous CO_2 standards, administering the science team for the Global Survey of CO_2 in the Oceans project, and maintaining a successful Small Business Innovative Research (SBIR) Program.

The ocean mixed layer is an important link between the general circulation of the ocean and the atmosphere. Mixing in the oceanic surface layer directly influences fluxes of heat, momentum, and greenhouse gases through the atmosphere-ocean interface. Our research includes a detailed analysis of ocean surface layer processes using both two- and three-dimensional nonhydrostatic ocean models. The results will be used to develop better representations of the ocean surface mixed layer that will be included in coupled atmosphere-ocean general circulation models.

A three-dimensional numerical model of deep convection in the open ocean is being developed. The two-dimensional version of the model has been used to begin the investigation into deep water formation. Construction of the three-dimensional convection model has been completed and the first tests of the code are under way. The three-dimensional model will be used to investigate more fully the process of convection and deep water formation, and to help develop improved parameterizations of deep convection in ocean general circulation models.

Whitecaps/CO_2 Gas Exchange research continues, and preliminary analysis of the data suggests that microwave radiometry remains a promising technique for remotely sensing gas exchange velocities at global-ocean scales.

Also in FY 1992, we completed additional studies and tests on the Autonomous, Expendable Conductivity, Temperature, and Depth probe (AXCTD) concept to answer questions raised in FY 1991 about the long-term stability of the conductivity sensors used in the prototype, and about the projected selling price of AXCTDs in large quantities. An "engineered" prototype AXCTD was built to demonstrate to potential funding agencies.

Progress

Surface Mixed Layer

In FY 1992, we completed a series of tests using the two-dimensional version of the nonhydrostatic ocean large eddy simulation model. We demonstrated that the model is capable of accurately simulating small-scale ocean processes, such as internal wave momentum transport, that are difficult to represent in large-scale ocean general circulation models. We also performed our first three-dimensional simulations of the ocean mixed layer. These tests included a case with realistic surface heating and wind stress. Overall, the model development phase of the study is near completion, with the remaining tasks directed toward implementation of surface wave effects and an open lower boundary condition.

Two-Dimensional Convection Model

The two-dimensional convection model has been improved by changing the method used to advect temperature and salt. This change has improved the model's ability to maintain strong gradients of temperature and salinity. The two-delta-x filter has been extended to filter horizontal and vertical velocities in both dimensions, thereby making the model more robust.

Three-Dimensional Convection Model

Construction of a three-dimensional convection model that uses the nonhydrostatic, Boussinesq, incompressible Navier-Stokes equations with full Coriolis forcing terms was completed. This model was based on the nonrotating two-dimensional model. The full advection scheme and turbulent kinetic energy (TKE) subgrid model has also been implemented. The three-dimensional convection model will be reorganized and converted to the CM Fortran dialect for use on the massively parallel CM-5 at Los Alamos National Laboratory.

Whitecaps/CO_2 Gas Exchange Research

A Whitecap Simulation Tank (WST) equipped with a computer-controlled tipping bucket mechanism to reproducibly generate bubble plumes with known bubble plume coverage (B_c) was designed and constructed at PNL/MSL during FY 1990. During FY 1992, several significant laboratory experiments to study the effects of bubble plumes on gas exchange were conducted in the WST. These include

- DMS transport experiments
- CO_2 transport experiments
- Helium transport experiments
- WST bubble concentration measurements.

In FY 1992, further processing of the microwave radiometer data from the 1991 Nantucket Shoals microwave/whitecap experiment allowed comparison of the time series for apparent microwave brightness temperature (σ) and fractional area whitecap coverage (W_c).

Also in FY 1992, the Lamont-Doherty Geological Observatory completed an analysis of water samples taken during the 1990 Georges Bank dual-tracer gas exchange experiment, allowing completion of the gas transfer calculations.

AXCTD Development

Eleven articles about the AXCTD and three papers for professional conferences were published in FY 1992. As a result of widespread media coverage, the AXCTD is now familiar to the scientific and ocean-engineering communities. With the goal of attracting private sector capital to make the AXCTD commercially available in large quantities, a patent application on the technology was successfully completed and the patent will be issued in April 1993.

FY 1992 Highlights

Surface Mixed Layer Results

Key results for FY 1992 include the simulation of internal waves and turbulence in the equatorial Pacific Ocean. Modeling the surface layer of the equatorial Pacific Ocean is challenging because of the strong vertical current shear and density stratification common to the region (Figure 1). The primary zonal current is the eastward-flowing Equatorial Undercurrent (EUC) at a depth of roughly 120 m, with a speed of about 1.5 ms^{-1} as shown in Figure 1. The EUC is forced by a zonal pressure gradient resulting from the westward-directed surface wind stress. Above the EUC, the wind stress directly forces the South Equatorial Current (SEC), which flows westward at a speed of about 0.5 ms^{-1}. The shear zone generated by these currents is marginally stable and exhibits a diurnal cycle of turbulence that depends on convection forced by surface cooling (e.g., Moum et al. 1989). In addition, surface convection forces internal gravity waves, which can transport momentum away from the surface current to deeper waters. We performed simulations of the EUC to examine the processes that create internal gravity waves and force the vertical transport of horizontal momentum.

We used a vertical temperature profile that was taken in April 1987 at a location on the equator near 135° W (Hebert et al. 1991). The domain size for the simulation was 1280 m x 250 m with 5-m resolution. A linear extrapolation was assumed for both temperature and velocity below 150 m. In the first experiment, a constant surface wind stress of 0.05 Nm^{-2} was prescribed with an idealized surface heat flux that represented typical conditions on the equator for April. A 3-day simulation period was chosen, allowing the model to adjust during the first day and still provide two full heating cycles for analysis.

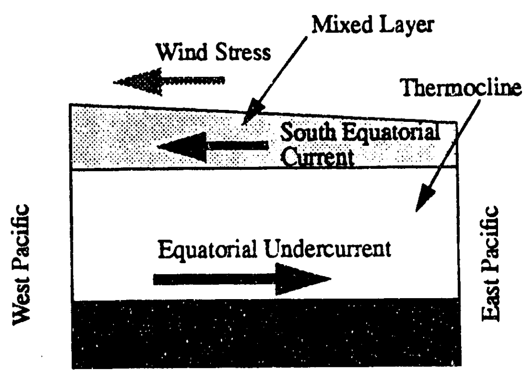

FIGURE 1. Schematic of the Equatorial Pacific Ocean Current System.

Figure 2 shows plots of the model vertical velocity and temperature structure for times representing surface heating and surface cooling from simulation day 2. The model reveals that the surface mixed layer and thermocline undergo a diurnal cycle, with internal waves active throughout the simulation. The character of these waves is strongly affected by the surface heating cycle, with wave strength increasing at night when surface cooling is at a maximum. The waves have a characteristic phase speed between -0.05 and 0.05 ms^{-1} and a wavelength of about 250 m; this dominant wavelength agrees with the time series analysis presented in Moum et al. (1992) for the 4-day period beginning April 14, 1987. The simulated wavelength and wave strength are similar to wave observations reported in Hebert et al. (1992).

A number of conceptual models have been proposed to explain the formation of internal waves in convective, sheared flow. The most popular hypothesis treats convective plumes as independent structures that act as obstacles to the mean flow, generating trapped internal waves. In the numerical model, this process is active only during the initial spin-up phase of the simulation. When internal waves are generated, the convection becomes a forced internal mode, which weakens during the daytime stabilization period but does not completely dissipate.

The key to the internal mode forcing is the presence of critical layers at depths of 35 and 175 m. A critical layer is formed when the mean horizontal current velocity equals the phase velocity of the internal wave field. Critical layers are important because they represent regions in the flow where the exchange of energy between the internal wave field and the background flow depends on the strength of the local hydrodynamic stability as measured by the Richardson number. In the simulation, the Richardson number in the upper critical layer drops below 0.25, creating an unstable gravity wave mode with energy transferred from the mean flow to the internal wave field. When

(a) Hour 24 (Sunset, Day 1)

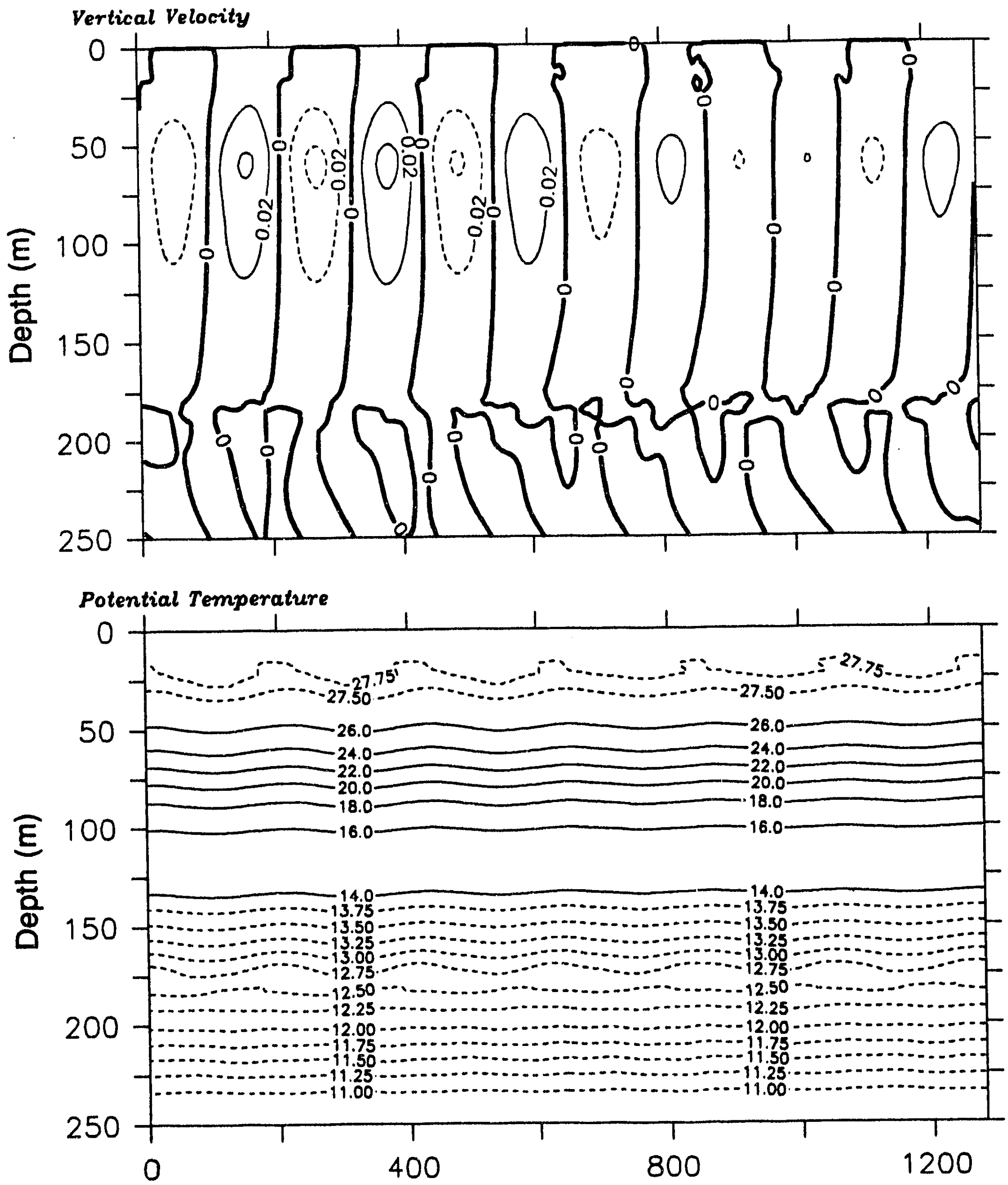

FIGURE 2. Vertical Velocity (top), Potential Temperature (middle), and Zonal Velocity (bottom) for (a) hour 24 and (b) hour 38, Representing a Daily Cycle. The contour interval for vertical velocity is 0.02 ms^{-1} for (a) and 0.04 ms^{-1}. Potential temperature is contoured every 2°C, with contours less than 14°C and greater than 27.5°C plotted as dashed lines every 0.25°C.

(b) Hour 38 (Early Morning, Day 2)

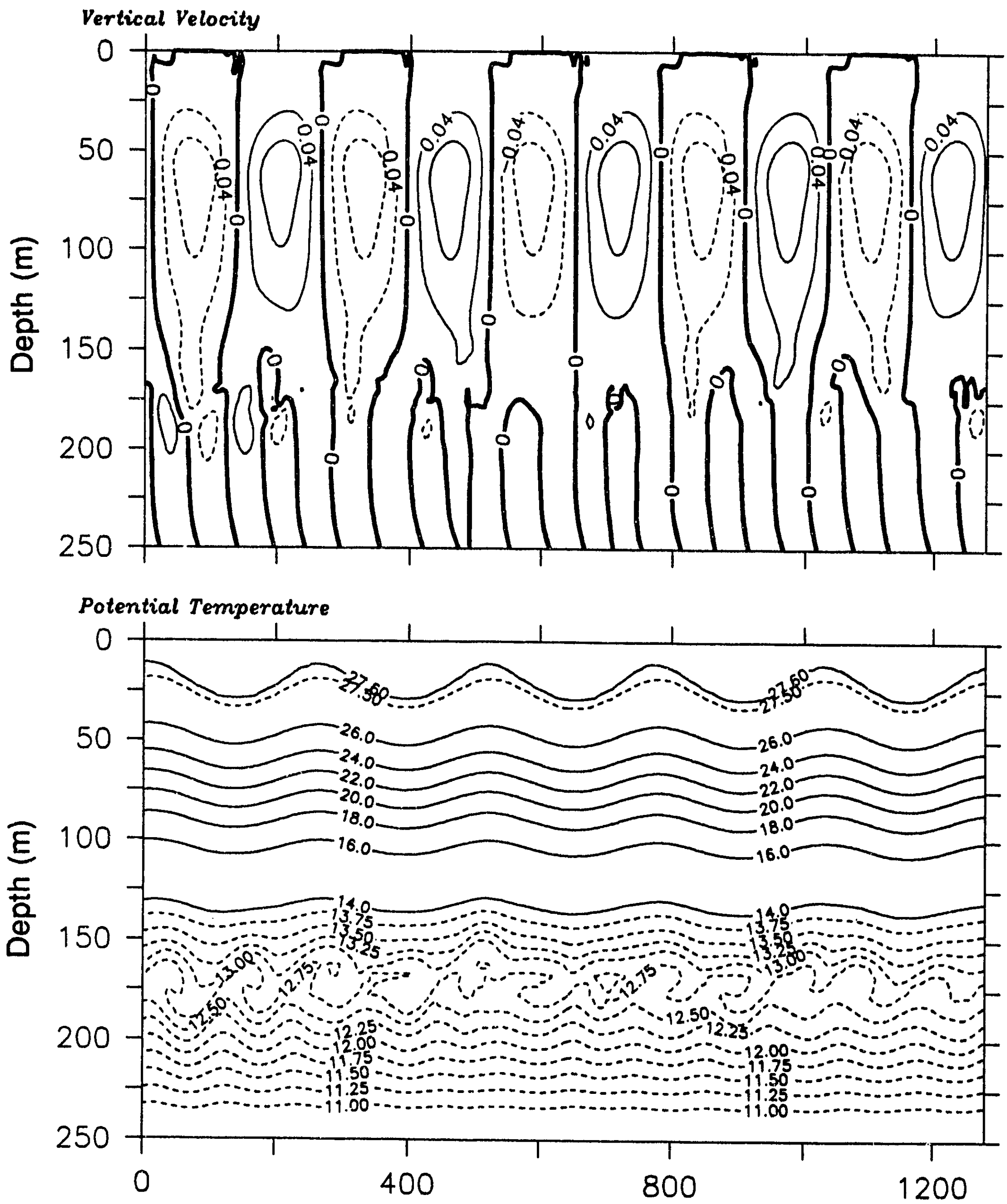

FIGURE 2. (contd)

surface heating is imposed, the Richardson number rises above 0.25 and the internal waves decrease in strength, acting as a drag to the mean flow near the critical layers. Because the magnitude of the wave drag is comparable to the turbulent dissipation rate and the large-scale zonal pressure gradient estimated by Hebert et al. (1991), the internal waves may play a significant part in the zonal momentum budget. The critical layer instability also promotes the generation of small-scale waves in the lower-level critical layer (Figure 2b) that are similar in appearance to Kelvin-Helmholtz billows. Measurements of turbulent dissipation taken beneath the EUC (Peters et al. 1988) demonstrate that turbulence exists below the EUC core and support the model results.

Our two-dimensional model results indicate that the representation of subgrid-scale disturbances in ocean general circulation models should include the effects of internal waves in equatorial regions. However, more detailed observations and model experiments are needed before an accurate parameterization can be developed. A journal article presenting a more complete description of these model results has been submitted to the *Journal of Oceanography.*

In addition to our work using the two-dimensional model, we performed preliminary three-dimensional simulations of an evolving surface mixed layer. The case we considered represents the northern Pacific Ocean, where the mixed layer is dominated by surface wind stress and the effects of the Earth's rotation. After 6 hours of cooling, the surface currents show banded regions of convergence and downward motion that divide larger-scale upwelling, divergent cells (Figure 3). These cells represent eddies on the scale of the mixed layer that actively transport heat and momentum from the ocean surface to the top of the thermocline. The influence of the surface

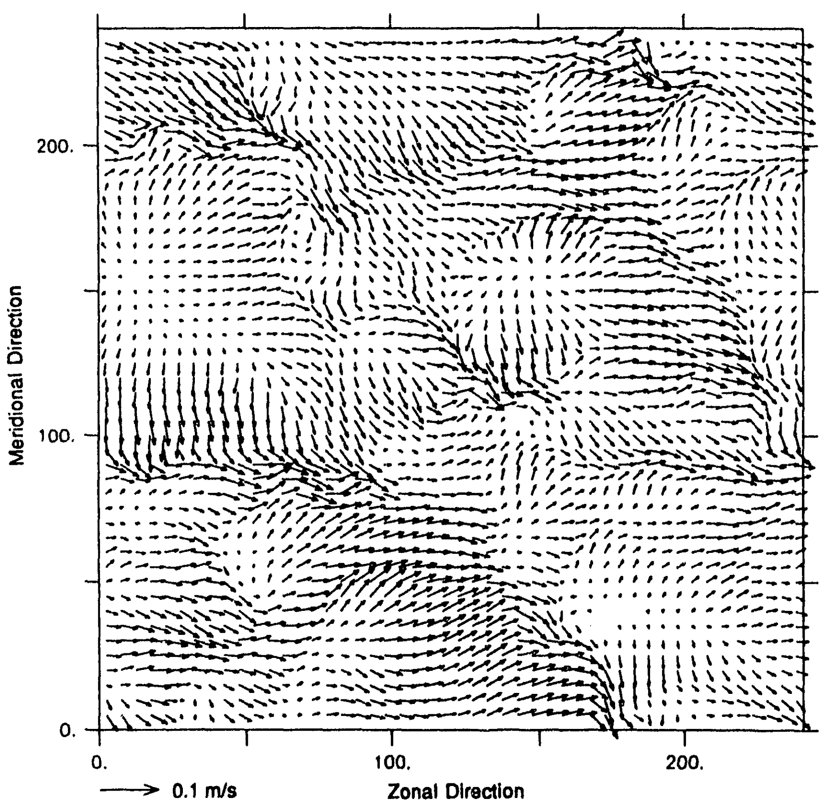

FIGURE 3. Horizontal Velocity After 6 Hours of Cooling. Note that areas of convergence are narrow and are biased in direction, following the imposed westerly surface wind stress.

wind stress is evident in the narrow convergent regions where the horizontal motion is, on average, in the same direction as the surface stress. This simulation demonstrates that the three-dimensional model can now be applied to more complex processes such as wave-driven circulations or Langmuir cells.

Two-Dimensional Model Results

A comparison of two ocean convection experiments using data from the Greenland Sea and Western Mediterranean Sea (MEDOC) was presented in poster format at the January 1992 Ocean Sciences meeting in New Orleans.

For the MEDOC experiment, the surface mixed layer grew uniformly. After 20 days of simulation, the mixed region filled the water column. After mixing, the model temperature and salinity were in good agreement with observations and the model velocities were only slightly larger than those observed.

For the Greenland Sea experiment, the surface mixed layer eroded rapidly to a depth of 1200 m between 11 and 12 days. This erosion was accomplished by a series of plumes, which is consistent with a thermobaric instability. Plumes do not form in experiments in which the thermobaric instability mechanism is removed from the equation of state for seawater.

The results of the MEDOC experiment are qualitatively similar to the simple convection of the validation experiment. The normalized heat flux profiles and horizontal wave-number spectra are consistent with mixed-layer growth by convection. The Greenland Sea experiment was very different, during plume generation, from the validation experiment. While plumes were forming, the heat flux was several times larger than that predicted by simple mixed-layer dynamics. When plume formation ended, the heat flux and horizontal wave-number spectra became consistent with mixed-layer growth by convection. There is a qualitative and quantitative difference in the two convection experiments because the thermobaric instability is more important in the Greenland Sea experiment.

Three-Dimensional Model Results

An abstract was submitted to the Fall 1992 American Geophysical Union meeting in San Francisco to present preliminary three-dimensional model results demonstrating the effect of Coriolis forces on deep convection. In the three-dimensional model both components of the Coriolis force have been included, and experiments in which these components are present or absent have been used to demonstrate the qualitative effects. The following summarizes the preliminary results.

A smoothed-temperature and salinity profile taken in February 1988 in the Greenland Sea and an idealized deep mixed-layer profile were used to initialize the model. Constant surface cooling of $-300\ Wm^{-2}$ was used to force the model. A snapshot at model day 4.25 taken from a 32^3 grid-point model run is shown in Figure 4.

For the nonrotating case, the horizontal wave number spectra of the velocity components and the temperature from the model results agreed favorably with theory for the inertial-convective subrange. Vertical profiles of normalized velocity and temperature variance were in good agreement with laboratory measurements. Convective plumes traveled straight downward; horizontal motions were radial outward from the plume.

With only the upward component of the Coriolis force present, the convective plumes traveled

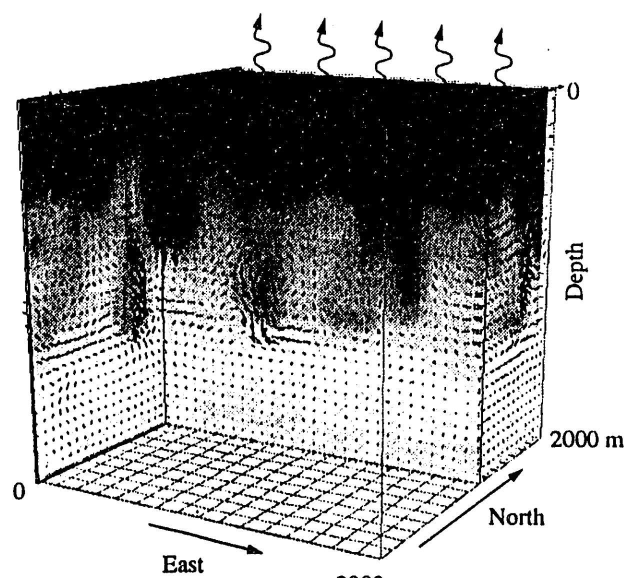

FIGURE 4. Model Day 4.25 from a Model Run Using an Initial Temperature-Salinity Profile Taken During February 1988 in the Greenland Sea. Dark gray represents the coldest temperatures and light gray the warmest.

straight downward with cyclonic horizontal motions. The vertical motions were weaker than in the nonrotating case. With both Coriolis components, the plumes slanted to the east as they descended. The horizontal motions associated with the plume were cyclonic, with an eastward velocity component superimposed.

Whitecaps/CO_2 Gas Exchange Research Results

Laboratory and field experiments have provided encouraging results. Significant findings and conclusions follow.

The Georges Bank dual-tracer gas exchange data set has provided evidence that the evasion rate (k_L) is linearly correlated with the fractional area whitecap coverage (W_c). There is very good correlation between k_L and W_c for the conditions present during the Georges Bank experiment. This data set demonstrates that it may be possible to predict k_L from W_c under oceanic conditions.

Data analysis from the Nantucket Shoals experiment has also continued during FY 1992. The data are encouraging because they demonstrate W_c can be correlated with remote measurements of σ.

The data from the controlled study of the microwave emissivity of bubble plumes using a dock-mounted tipping bucket and radiometer has shown that bubble plumes generated by simulated waves act as blackbody sources of microwaves. The data further suggest that the microwave radiometer is responding to the presence of bubble plumes in the water column. These results are important in developing whitecap coverage retrieval algorithms for use with satellite-mounted microwave radiometers.

For both CO_2 invasion and evasion into or out of seawater, excellent linear correlation has been observed between k_L for CO_2 and WST bubble plume coverage (B_c) for T_W = 20°C. Similar results were obtained for T_W = 5°C, 10°C, and 15°C. The bubble plumes in the WST were observed to increase k_L by a factor of 10 over the range of B_c studied here. Because the maximum B_c possible in the WST corresponds to a wind speed of approximately 15 ms^{-1}, this large effect of bubbles on promoting air/water exchange of CO_2 suggests that oceanic breaking waves could have a large role in determining the air/sea flux of CO_2 at high wind speeds.

Developing an accurate predictive model for k_L in terms of B_c requires knowing how changes in Schmidt number (S_c) and aqueous-phase solubility (α) affect air/water transport governed by bubble plumes. Varying S_c and α is most easily done by changing the chemical species to be studied. He and O_2 are of particular interest because they provide a wide range of S_c and α values. Using k_L for He and O_2 as a function of B_c in the WST for water temperatures of 5°C and 20°C, excellent linear correlation is observed between k_L and B_c for both gases. These data, along with the CO_2 data, will be used to develop a model for predicting k_L from B_c, S_c, and α. This model can then be tested using data collected during the outdoor wave basin experiment to be performed in early FY 1993.

Originally, dimethyl sulfide (DMS) measurements were made in the WST to provide more information concerning the Schmidt number and solubility dependence of gas exchange driven by bubble plumes. However, the DMS k_L measurements made in FY 1991 and FY 1992 have provided data suggesting that the transport of DMS at an air/seawater interface is gas-phase rate-controlled. The observed behavior of DMS is typical of a gas with partial or total gas-phase rate control. Because current methods for predicting k_L from wind speed were developed for compounds that are liquid-phase rate-controlled, predictive models for k_L of DMS may be inappropriate and lead to inaccurate gas exchange velocities. This is important in modeling the diurnal cycling of DMS in the remote marine environment and predicting global air/sea fluxes of DMS.

The phased-Doppler anemomenter (PDA) was used to further study bubble size distributions and depth-dependent concentrations in the WST. The results from the PDA calibration procedure and comparison of preliminary WST bubble measurements were submitted for publication as a peer-reviewed paper to the *Journal of Geophysical Research.*

AXCTD Development

To reduce the manufacturing costs of the AXCTD pressure housing, including the tube and end caps, two pressure housing designs were tested, one based on ceramics and the other on a composite material. A series of cyclic and full-pressure hydrostatic tests was also completed with the ceramic tubes. The main objective of these tests was to increase the buoyancy-to-weight ratio to reduce the underwater package size. Prior to hydrostatic testing, the end cap and tube configurations were investigated using commercially available stress analysis models to determine where stress concentrations might cause failure. The results of both the modeling and hydrostatic tests are encouraging. We verified that the simplest end cap design and most convenient elastomer perform satisfactorily at 8000 psig (5400 m depth), and that the stress analysis model did an excellent job of predicting where material failure would occur.

Also in FY 1992, a pressure vessel with a hydraulic control system was built to perform long-term immersion tests of conductivity-temperature-depth (CTD) sensors in standard seawater at full operating pressure. The pressure vessel is rated to 10,000 psig and has a pressure-balanced, inert plastic liner to isolate the seawater bath for the sensors from the structural stainless steel parts of the vessel. This unique feature drastically reduces the risk of crevice corrosion in the hydraulic system and permits deionized water to be used for a working fluid.

The system is pressurized by a high-pressure, liquid chromatography solvent pump and has the "mexican jumping bean" system for stirring the seawater bath. A pulsed DC electromagnet and a teflon-coated magnet agitate the bath without having to penetrate the pressure vessel wall with a rotating shaft. The transfer standards for temperature and pressure are the platinum resistance thermometer and the quartz piezoelectric pressure transducer, both well-accepted by the scientific community. Construction and functional tests of the pressure vessel and control system are complete.

Plans for FY 1993

Surface Mixed Layer

Completion of the three-dimensional model will allow us to examine in detail the processes that affect the growth and maintenance of the ocean surface mixed layer. We plan to implement a Stokes drift surface wave parameterization so comparisons can be made between mixing with and without surface waves. Tests will also be performed to examine the effects of current shear and wave direction on the formation of circulations within the mixed layer. The results of these experiments will be compared with observations to verify the accuracy of the model.

Two-Dimensional Model

In FY 1993, the paper now in preparation presenting results from the two-dimensional model will be completed and submitted to a refereed journal for publication.

Three-Dimensional Model

Additional testing and model verification experiments will be performed on the three-dimensional model. The model will be ported to the CM-5 and optimized for a data parallel implementation. Experiments will be performed to examine the sensitivity of deep convection on various environmental conditions, cooling rate, pre-conditioning, wind stress, and temperature and salinity structure.

Whitecaps/CO_2 Gas Exchange Research

Ongoing research efforts will include both laboratory and field experiments designed to further develop the capability to predict k_L for CO_2 from remote measurements of microwave apparent brightness temperature. The PDA will be used to make more detailed measurements of the bubble concentrations, motion, and turbulent structure associated with the tipping-bucket-generated bubble plumes in the WST. The WST bubble measurements will be used in applying and developing bubble-plume-driven air/water gas transport models. The WST will be used to measure k_L for

SF_6. These data will help in interpreting gas exchange data collected during the outdoor wave basin and oceanic dual-tracer experiments, and will be valuable in developing an empirical parameterization of k_L in terms of bubble-plume coverage, Schmidt number, and aqueous-phase solubility. A large outdoor wave basin capable of generating breaking waves will be used to conduct a concurrent gas exchange/passive microwave radiometry experiment, which will allow k_L, brightness temperature, and whitecap coverage to be measured simultaneously under known, reproducible conditions. These data will be useful in developing a relationship between k_L and whitecap coverage that can be tested in later oceanic experiments.

AXCTD Development

We anticipate that CTD stability tests will commence in January 1993 and continue for a minimum of 6 months. The demonstration model AXCTD will be ready for use at about the same time. During the coming year, we hope to complete negotiations with a private company to license the AXCTD technology for commercial use. If we are successful, the AXCTD will become widely available to the scientific community for global studies of ocean climate.

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Improved Parameterization for Deep Convection Processes in Ocean General Circulation Models

T. Paluszkiewicz, E. D. Skyllingstad, and D. W. Denbo

Investigators at PNL are developing a parameterization for deep convection in Ocean General Circulation Models (OGCM). The goal of this research is to improve the model physics governing deep convection and deep water formation. The ultimate goal is to incorporate the improved physics into the OGCM used in global climate research, and consequently improve the simulation of the deep water production process that is important to the carbon cycle and climate modeling.

Several OGCMs were evaluated and the Modular Ocean Model (MOM) (Pacanowski et al. 1991) and Parallel Ocean Climate Model (POCM) (Semtner and Chervin 1988) were selected for parameterization and sensitivity tests of penetrative convection in the Nordic Seas. The Nordic Seas include the Greenland, Iceland, and Norwegian Seas as shown in Figure 1. The configuration of the model domain was completed and a series of sensitivity tests has been prepared. Development of the one-dimensional convection model has begun with initial studies on the entrainment rate and penetrative plume time-scale using a nonhydrostatic model of deep-convective plumes (Denbo and Skyllingstad 1992).

Project Goals and Objectives for FY 1992

The goals and objectives for this past year were the following:

- to evaluate and obtain the OGCM, investigate candidate ice models, and select the mixing-layer dynamics scheme
- to assemble and configure the OGCM and other models for a closed basin the size and shape of the Nordic Sea

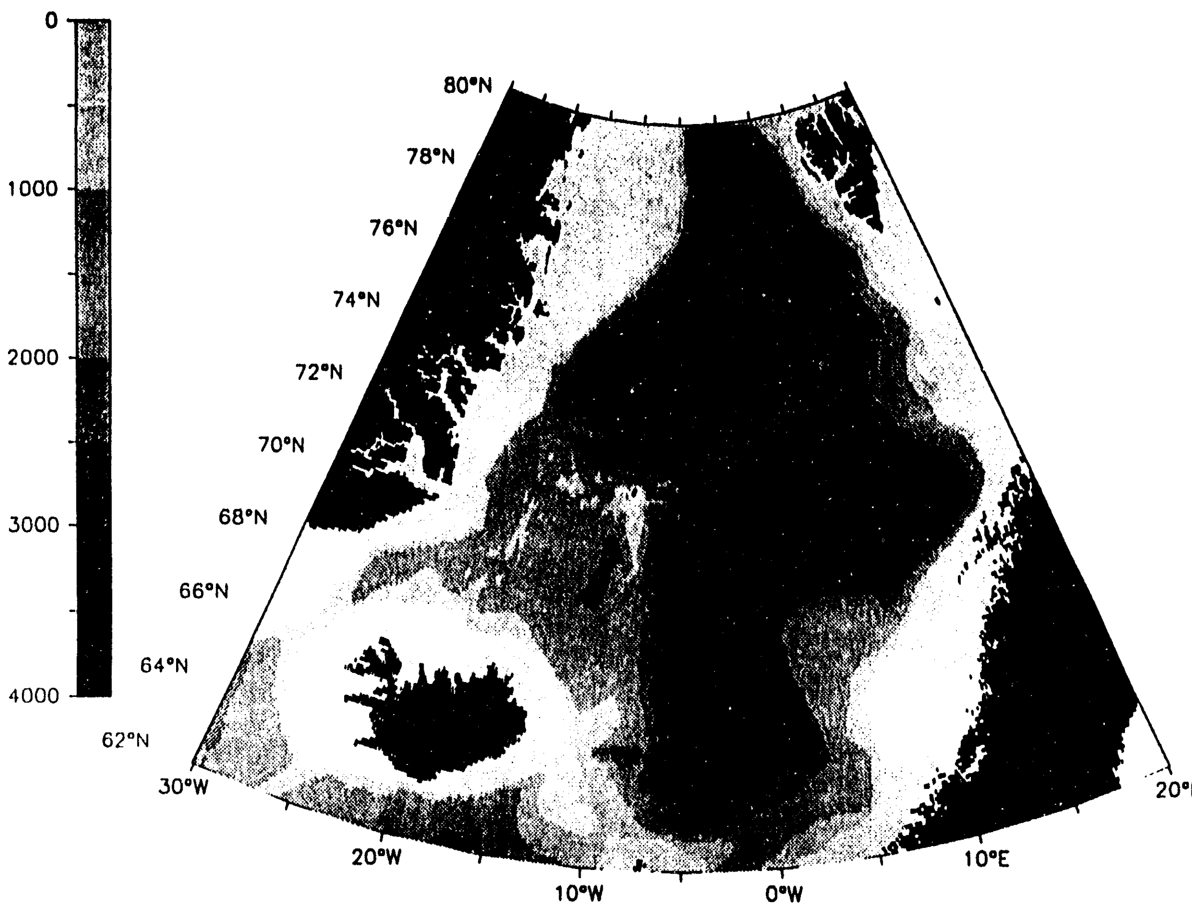

FIGURE 1. Nordic Seas Bathymetry (meters).

- to obtain data from high latitude regions for constructing the three-dimensional initial conditions and for initializing the one-dimensional parameterization. Potential sources of data include the seasonal climatology of Levitus and the National Ocean Data Center as well as other investigators.
- to formulate and construct the one-dimensional penetrative convection parameterization.

FY 1992 Accomplishments

OGCM Experiments

MOM and POCM were selected for use in the OGCM experiments following consultations with other Computer Hardware, Advanced Mathematics, and Model Physics Program (CHAMMP) science team members at Los Alamos National Laboratory and the National Center for Atmospheric Research (NCAR). The two models are sufficiently similar and include several options for parameterizing mixing. Both MOM and POCM can use the mixing scheme used by Semtner and Chervin (1992); consequently, similar model configurations can be used in the parameterization research as are now being used in the global-scale simulations. As the parameterization develops, it may be necessary to use a mixing scheme that allows more complexity. If this need occurs, MOM has the turbulence closure scheme of Mellor and Yamada (1982) as an option.

The primary objective in the OGCM experiments is to generate circulation and temperature-salinity fields that represent the preconditioning period before deep convection occurs. The model domain for the OGCM simulations is the Nordic Seas between latitudes 62° to 80°N and longitudes 15°W to 20°E. The domain includes the Norway and Loften Basins and, most importantly, the Greenland and Boreas Basins as well as the Mohns and Knipovich Ridge systems (Figure 1).

The topography was derived from the ETOP5 data set. For the initial simulations, a smoothed topography was created that maintains the geometric shapes of the basins and ocean ridges but simplifies coastlines, the ridge topography, and eliminates Jan Mayen Island (Figure 2). This domain was created for the first simple basin-scale circulation simulations from which the preconditioning and parameterization studies began. Initialization fields were constructed from the Levitus climatology. We conferred with other CHAMMP science team members about the possibility of using a restart file from previous runs to initialize the simulations and thereby obtain a more realistic basin-scale circulation at less computational cost.

The horizontal and vertical resolution of the model is a subset of the configuration used by other CHAMMP science teams. We are performing sensitivity analysis to identify the most flexible configuration in run-time efficiency and compatibility with other CHAMMP simulations. The horizontal resolution will be either 1/2 or 1/4 degree and there will be 20 levels in the vertical with the same distribution as in Semtner and Chervin (1992).

Development of the One-Dimensional Deep Convection Model

The parameterization scheme for oceanic deep convection is derived from the atmospheric scheme for cumulus convection that was developed by Fritsch and Chappell (1980). The parameterization relates the amount of convection to the instability of the water column as defined by the nonlinear equation of state and the surface mixed layer. The buoyant energy of the grid volume is

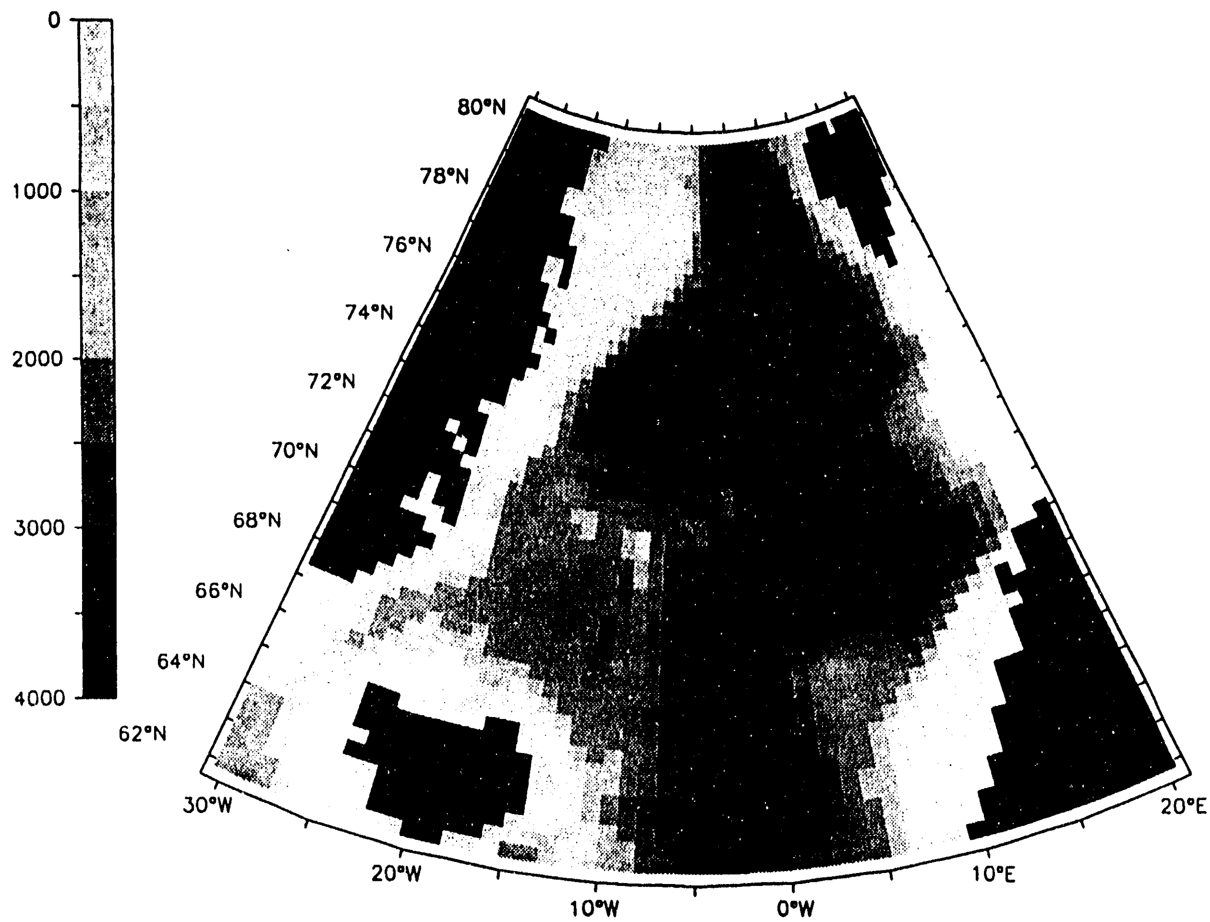

FIGURE 2. Nordic Seas Bathymetry (meters), Low Resolution.

minimized by generating enough downward penetrative and upward compensating motions to balance the unstable density profile. We have begun to test the parameterization by constructing a one-dimensional model based on physical principles, but requiring empirical estimates of some parameters such as entrainment rate, plume time-scale, and plume volume. Because few observations are available, we will estimate these parameters from the three-dimensional, nonhydrostatic plume model of Denbo and Skyllingstad (1992). The three-dimensional plume model has been developed to a point enabling the run of canonical experiments to generate the entrainment and time-scale parameters needed to further develop the one-dimensional model and parameterization scheme.

Coordination with CHAMMP

During this first year of research, coordination with other CHAMMP science teams began. It is our goal to stay current on the OGCM model developments within CHAMMP so the parameterization scheme will be constructed for the appropriate model and address the program goals. We have contacted CHAMMP science team members at Los Alamos National Laboratory, NCAR, and Lawrence Livermore National Laboratory. During the 1992 Science Team Meeting, and most recently at the CM5 class at Los Alamos, researchers met with key science team members to determine which model code and configuration would be most appropriate for the OGCM simulations in support of the parameterization studies. In October, we met with Dr. Chervin from NCAR to further explore the use of the POCM code and to discuss the existing and future simulations.

Plans for FY 1993

OGCM Experiments

In FY 1993, a series of experiments with the OGCMs will be conducted to generate a base-case circulation that has the dominant properties of the Nordic Seas circulation and the water column conditions appropriate for the preconditioned phase of deep convection. The experiments will use idealized and realistic forcing scenarios and different mixing schemes. To accelerate this phase of the research, we will confer with the CHAMMP science team members about the feasibility of using existing model archives for the initialization field for the Nordic Seas simulations. As much as is possible, model experiments will use the same mixing scheme and forcing as in Semtner and Chervin (1992), which will serve as a basis for comparison. Several sensitivity tests are planned to determine the role of topography, response to the wind field, and sensitivity to the mixing parameterization in preconditioning the basin for deep penetrative mixing. We will incorporate the one-dimensional model into the base-case simulation to test the parameterization of deep convection.

One-Dimensional Deep Convection Model Development

We will construct a one-dimensional model for oceanic deep convection based on Fritsch and Chappell (1980) and will test the model by applying it to a number of density profiles that represent conditions in the Nordic Seas. Surface cooling will be applied over a time period representing typical synoptic weather events. Comparisons will be made between the resulting profiles and the profiles generated by the three-dimensional, non-hydrostatic large eddy simulation initialized using the same conditions. These comparisons will test the effects of the simplified physics and allow for calibration of tunable parameters such as the entrainment rate, plume time scale, and areal plume coverage. After these tests have been completed satisfactorily, the one-dimensional parcel model will be incorporated into the OGCM used for base-case simulations.

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