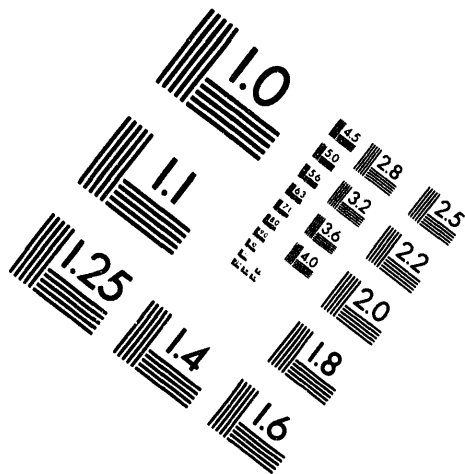
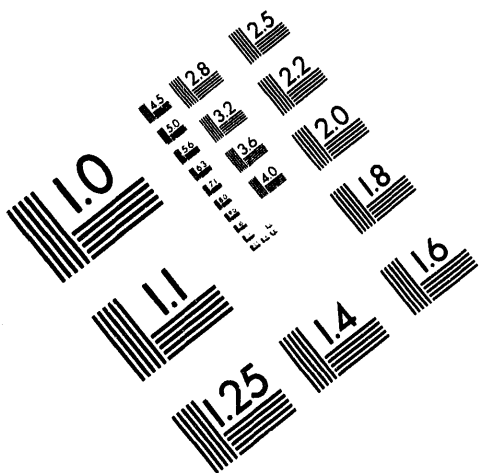




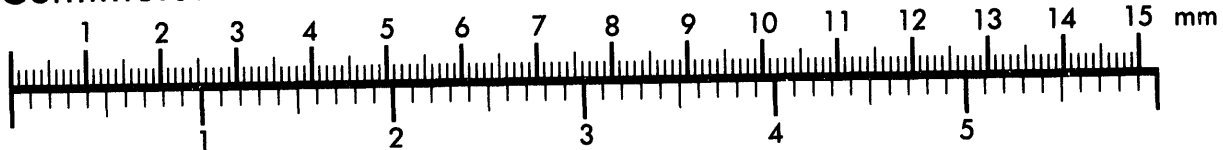
**AIM**

**Association for Information and Image Management**

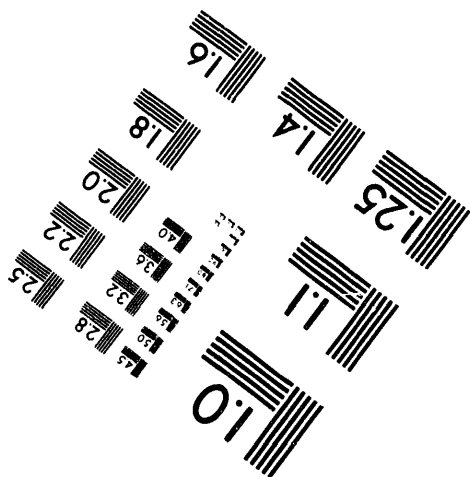
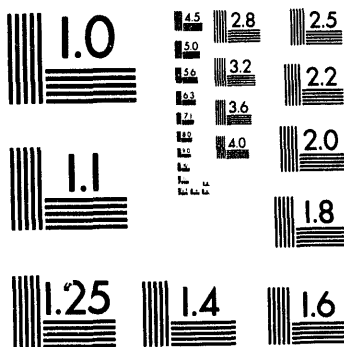
1100 Wayne Avenue, Suite 1100  
Silver Spring, Maryland 20910  
301/587-8202



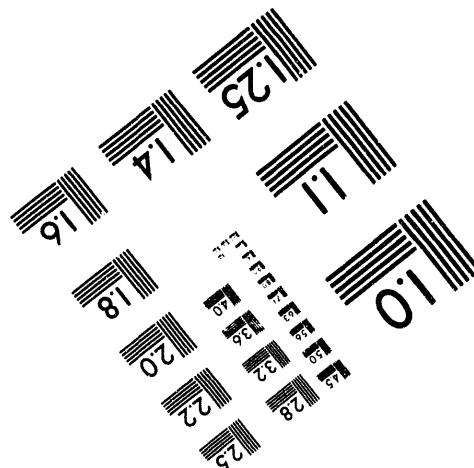
**Centimeter**



**Inches**



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**1 of 2**

**Pacific Northwest Laboratory  
Annual Report for 1993 to the  
DOE Office of Energy Research**

**Part 3: Atmospheric and Climate Research**

Staff Members  
of Pacific Northwest Laboratory

May 1994

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

Pacific Northwest Laboratory  
Richland, Washington 99352

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## Preface

This 1993 Annual Report from Pacific Northwest Laboratory (PNL) to the U.S. Department of Energy (DOE) describes research in environment and health conducted during fiscal year (FY) 1993. 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 (OHER) within the Office of Energy Research. In some cases, 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 multi-disciplinary nature of the research effort.

The parts of the 1993 Annual Report are as follows:

**Part 1: Biomedical Sciences**

J. F. Park, Program Manager  
A. L. Brooks, Report Coordinator  
C. C. Lumetta, Editor

**Part 2: Environmental Sciences**

R. E. Wildung, Program Manager  
L. K. Grove, Editor

**Part 3: Atmospheric Sciences**

W. R. Barchet, Program Manager  
B. V. Johnston, Editor

**Part 4: Physical Sciences**

L. A. Braby, Program Manager  
S. L. Downs, Editor

Activities of the scientists whose work is described in this annual report are broader in scope than the articles indicate. Throughout the year, PNL staff have responded to numerous requests from DOE 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  
Manager, Health and Environmental Research Program



**Previous Annual Reports in this series:**

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

## Foreword

The U.S. Department of Energy's (DOE's) Office of Health and Environmental Research (OHER) atmospheric sciences and carbon dioxide research programs 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 implementation of the Energy Policy Act of 1992. This volume reports on the progress and status of all OHER atmospheric science and climate research projects at the Pacific Northwest Laboratory (PNL).

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

Research at PNL provides basic scientific underpinnings to DOE's program of global climate research. Research projects within the core carbon dioxide and ocean research programs are now integrated with those in the Atmospheric Radiation Measurements, the Computer Hardware, Advanced Mathematics and Model Physics, and Quantitative Links programs to form DOE's contribution to the U.S. Global Change Research Program. Climate research in the Environmental Sciences Division 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 fiscal year 1993 in each of these areas. A divider page summarizes the goals of each area and lists the projects that support research activities.

## Contents

<b>Preface</b> . . . . .	iii
<b>Foreword</b> . . . . .	v
<b>Atmospheric Research</b>	
Continental and Oceanic Fate of Pollutants, C. M. Berkowitz, R. D. Saylor, K. M. Busness, E. G. Chapman, W. J. Shaw, and J. M. Thorp . . . . .	1
Research Aircraft Operations, K. M. Busness, O. B. Abbey, W. A. Garrity, R. V. Hannigan, and M. J. Warren . . . . .	6
ASCOT Program Scientific Direction, J. C. Doran . . . . .	8
Atmospheric Diffusion in Complex Terrain, K. J. Allwine and J. M. Hubbe . . . . .	11
Direct Simulation of Atmospheric Turbulence, J. C. Doran . . . . .	15
Interactions Between Surface-Exchange Processes and Atmospheric Circulations, W. J. Shaw . . . . .	18
Coupling/Decoupling of Synoptic and Valley Circulations, C. D. Whiteman, M. Furger, R. K. Hauser, S. Zhong, and X. Bian . . . . .	21
<b>Climate Research</b>	
The Atmospheric Radiation Measurement (ARM) Program: Field Measurements for Radiation Forcing and Feedbacks in General Circulation Models, T. S. Cress and G. M. Stokes . . . . .	25
Point-Area Relationships for Global Climate Models, J. C. Doran, C. D. Whiteman, K. J. Allwine, X. Bian, M. Furger, and J. Wilczak . . . . .	43
A Stratiform Cloud Parameterization for General Circulation Models, S. J. Ghan, L. R. Leung, R. C. Easter, J. E. Penner, C. C. Chuang, and J. McCaa . . . . .	47
Photometric Studies of Clouds from an Atmospheric Radiation Measurement Site, C. D. Whiteman, J. M. Alzheimer, G. A. Anderson, and W. J. Shaw . . . . .	51
Characterization of Cloud/Aerosol Interactions with Solar and Long-Wave Radiation, N. S. Laulainen, J. J. Michalsky, L. C. Harrison, N. R. Larson, and J. L. Berndt . . . . .	53
Second Generation Model, J. A. Edmonds . . . . .	61
Carbon Dioxide Ocean Research, J. P. Downing, W. E. Asher, D. W. Denbo, and E. D. Skyllingstad . . . . .	63
Improved Parameterization for Deep Convection Processes in Ocean General Circulation Models, T. Paluszkiwicz, R. D. Romea, E. D. Skyllingstad, D. W. Denbo, L. F. Hibler, and K. Strauss . . . . .	65

## **Publications and Presentations**

Publications . . . . .	69
Presentations . . . . .	75
<b>Author Index . . . . .</b>	<b>81</b>
<b>Distribution . . . . .</b>	<b>Distr.1</b>



## Atmospheric Research

Atmospheric research at PNL occurs in conjunction with the Atmospheric Chemistry Program (ACP) and with the Atmospheric Studies in Complex Terrain (ASCOT) Program that are managed by OHER's Environmental Sciences Division.

PNL has had a long history of program leadership in DOE atmospheric chemistry research. FY 1993 was the first year in which the scientific director of the ACP was not at a DOE laboratory. Dr. Jeremy M. Hales officially left PNL early in the year but continued as the science director of the ACP. PNL staff continued to provide direct support to Dr. Hales and the ACP in many ways. Major contributions are made to the ACP Monthly Update newsletter, which is distributed by PNL. The "Some Literature Insights, Notes, and Nuances" column, a regular feature of the newsletter, is produced at PNL. This column presents overviews of important topics in atmospheric chemistry that are being discussed in the current scientific literature. PNL staff regularly interact with DOE staff on emerging scientific issues pertaining to air quality, global chemistry, and ozone. Major ACP planning documents were produced for DOE with the assistance of PNL staff: *Overview of the DOE Atmospheric Chemistry Program's Ozone Project* (DOE/ER-0575T) and *Atmospheric Chemistry Program Program Operation Plan* (DOE/ER-0586T). Support for non-DOE scientists to participate in ACP planning exercises and field studies was provided through PNL.

ACP research at PNL focuses on the fate of energy-related pollutants as they are transported and processed in the atmosphere. In FY 1993, a major field study using the Gulfstream 1 research aircraft investigated photochemical processes controlling ozone distributions over the western North Atlantic Ocean. Chemical modeling studies and analyses of field study data from FY 1992 and FY 1993 are focusing on the contribution of various ozone production and destruction processes to the formation of the observed vertical profiles of ozone concentrations in the lower troposphere.

PNL conducts diversified research to support the ASCOT Program. A multiyear strategic plan for ASCOT was a major accomplishment of this, the fifth, year that the scientific director of the program was at PNL. All of PNL's ASCOT projects contribute to the ASCOT focus on understanding the complex boundary layer flow patterns that affect DOE's Rock Flats Plant near Denver, Colorado. However, many projects address the processes by which complex terrain and energy exchanges over heterogeneous surfaces govern the interaction of local airflows with large-scale synoptic circulations in other areas such as DOE's Hanford Site near Richland, Washington; the Oak Ridge, Tennessee area; and the Grand Canyon and Colorado Plateaus and Basins area in Arizona and Utah. Field studies, emphasizing remote measurements of boundary layer structure, analytical studies of new and historical data sets, and numerical modeling were applied to gain information and improve the understanding of these phenomena.

The following articles present summaries of the progress in FY 1993 under these research tasks:

- Continental and Oceanic Fate of Pollutants
- Research Aircraft Operations
- ASCOT Program Scientific Direction
- Atmospheric Diffusion in Complex Terrain
- Direct Simulation of Atmospheric Turbulence
- Interactions between Surface Exchange Processes and Atmospheric Circulations
- Coupling/Decoupling of Synoptic and Valley Circulations

## **Continental and Oceanic Fate of Pollutants**

**Principal Investigators:** C. M. Berkowitz, R. D. Saylor, K. M. Busness, E. G. Chapman, W. J. Shaw, and J. M. Thorp

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

A major emphasis of research activities during FY 1992 and FY 1993 was an investigation of the production and distribution of ozone over the western North Atlantic Ocean. PNL scientists carried out two major field programs over 2 years to evaluate the potential for long-range transport of ozone that originated from North American emissions of oxides of nitrogen and volatile organic compounds (VOC). This investigation consisted of modeling work and analysis of the data collected during the field programs. A secondary effort of PNL scientists involved modeling studies of anthropogenic aerosol distribution over the North Atlantic Ocean.

---

### **FY 1993 Accomplishments**

The primary objective for FY 1993 was to complete a measurement campaign over the western North Atlantic Ocean and coordinate PNL measurements with other institutes participating in the multiagency North Atlantic Regional Experiment. The broad goal of this program is to evaluate the fate of energy-related pollutants as they move over the ocean. Other organizations involved in this 1-month study included the National Oceanic and Atmospheric Administration (NOAA), the Canadian Atmospheric Environment Service (AES), the National Center for Atmospheric Research, Brookhaven National Laboratory, and a number of universities. PNL staff worked closely with scientists from the University of Minnesota, Lamont-Doherty Geophysical Observatory of Princeton University, and the State University of New York at Old Westbury (SUNY-Old Westbury).

A secondary objective for FY 1993 was to analyze the field data gathered over the western North Atlantic Ocean during FY 1992. This analysis is being carried out using both statistical

methods and modeling studies to assist in the interpretation of field study results. A final objective was to develop a capability to analyze field study data using a three-dimensional atmospheric chemistry and transport model.

PNL scientists flew a total of 82 h with PNL's Gulfstream I (G-1) aircraft to collect data on ozone, peroxides, radon, sulfur dioxide, and aerosols over the eastern and northern parts of the Gulf of Maine. Data collected during the 1-month field campaign will be used in conjunction with observations taken at Yarmouth by NOAA and the Canadian AES to describe changes in the chemical properties of air moving eastward from the coast of North America.

As part of its mission to foster new measurements capabilities, PNL's G-1 carried instrumentation designed by Dr. Judy Weinstein-Lloyd (SUNY-Old Westbury) to measure peroxides and charcoal filters designed by Dr. Fritz Zaucker (Lamont-Doherty) to measure radon gas.

The measurements of gas-phase peroxides were made using the recently developed non-enzymatic method, based on the fluorescence of

hydroxybenzoic acid produced from Fenton's reagent in conjunction with the p-hydroxyphenyl-acetic acid/oxidase technique for total peroxides. Both methods were also applied to the determination of peroxides in cloudwater by Ms. Cathy Banic from the Canadian AES. The measurements were taken in both clean air and polluted regions using the instrumentation onboard PNL's G-1. Clean-air peroxide concentrations averaged approximately 2 ppb, but concentrations as high as 9 ppb were observed, concomitant with ozone concentrations in excess of 100 ppb in shallow layers over the ocean south and west of Halifax, Nova Scotia. Measurements obtained from instruments both on the aircraft and on the ground indicate that total peroxide is predominantly hydrogen peroxide, with some contribution from methyl hydroperoxide and little, if any, hydroxymethyl hydroperoxide.

Approximately 100 samples of  $^{222}\text{Rn}$  were taken during 12 flights using a recently developed sampling system designed by Dr. Zaucker. This new sampling system allowed up to 12 samples to be taken on each flight by adsorption of radon onto activated charcoal, which was subsequently extracted and measured at the Halifax airport. Although all results must be considered preliminary at this time, Dr. Zaucker reports that near-surface concentrations were approximately 100 decays/min/m<sup>3</sup> over or near land and very low concentrations (5 to 10 decays/min/m<sup>3</sup>) were found at 300 ft when the G-1 was flying over the ocean. Surprisingly high concentrations (approximately 80 decays/min/m<sup>3</sup>) were observed at 5500 ft. In several flights, a minimum of 20 decays/min/m<sup>3</sup> were measured at 10,000 ft, with the  $^{222}\text{Rn}$  concentration increasing to 30 decays/min/m<sup>3</sup> at 18,000 ft.

Unusually high  $^{222}\text{Rn}$  concentrations occurred simultaneously with high pollutant concentrations (e.g., sulfur dioxide). This has been taken as confirming the applicability of  $^{222}\text{Rn}$  as a tracer

for defining the "continentality" of air masses. ACP scientists are considering a more extensive  $^{222}\text{Rn}$  program that would include more detailed measurements of the radon flux off the continent, thus allowing estimates to be made of the relative mixing of continental and maritime air masses.

Prior to PNL's participation in the FY 1993 study, a major effort was directed at analyzing results from last year's field program. Results from 20 aircraft flights between August 21 and September 14, 1992, over the North Atlantic Ocean were examined. Measurements of ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and total aerosol backscatter were taken between 90 m and 2.5 km above the sea surface, extending over an 800-km radius from Halifax.

The mean ozone-mixing ratio was found generally to be greater above the top of the mixed layer than near the sea surface. Measurements of nitrogen dioxide showed a similar tendency. No such trend toward greater values aloft were noted for carbon monoxide or backscatter. In almost all cases where elevated concentrations of ozone aloft were found, there was a well-defined boundary layer below. Synoptic meteorological analyses indicate that the greatest ozone-mixing ratios occurred in the free troposphere when the sampling domain was under the influence of westerly flows from populated North America. This pattern was not observed within the marine boundary layer. Possible mechanisms to account for the difference in the mixing ratio of ozone within and above the boundary layer over the western North Atlantic Ocean include the following:

- transfer of ozone from the stratosphere
- source regions that are significantly different for air at different elevations
- air mass aging



- effect of clouds on gas-phase chemistry through the dissolution of soluble species and aqueous-phase loss mechanisms
- reductions in solar radiation below a cloud layer.

Evidence was also found to suggest that ozone associated with anthropogenic sources can be transported significant distances within the boundary layer.

On several flights during the 1992 field work in Halifax, a quadrupole mass spectrometer (Trace Atmospheric Gas Analyzer [TAGA]) was operated in a fast sampling mode in an effort to measure turbulent fluctuations of dimethylsulfide (DMS) (Berkowitz et al. 1993; Busness et al. 1993). At the same time, the gust probe sampled turbulent variations in vertical velocity. During 1993, the high-frequency (up to 5 Hz) behavior in these two variables was analyzed to determine whether their covariance (the so-called eddy-correlation technique) can be used to yield a direct measurement of vertical flux of DMS (or other trace species measured by the TAGA) resulting from turbulence. Data were sampled at a rate of  $100\text{ s}^{-1}$ , averaged to  $10\text{ s}^{-1}$ , and analyzed using Fourier time-series analysis techniques. Power density spectra of vertical velocity showed expected behavior, based on well-established performance characteristics for the gust probe installed on the G-1 aircraft. The time series from straight and level flight legs within the atmospheric boundary layer suggest that there was considerable high-frequency noise in the DMS data, and this was confirmed by the power density spectra. Profiles of DMS from the surface to altitudes above the atmospheric boundary layer showed relatively large values of DMS within the atmospheric boundary layer and an appropriately rapid decrease through the capping inversion to significantly smaller free atmosphere values.

Following the field work in Halifax in 1992, scientists from PNL and Argonne National

Laboratory collaborated on a comparison of rapid response measurements of sulfur dioxide from the TAGA aboard the G-1 with rapid response total sulfur sensors mounted at the 150- and 250-m levels of the Boulder Atmospheric Observatory Tower near Boulder, Colorado. The sulfur dioxide time series and spectra from the TAGA for those flights show much the same behavior as those for DMS collected over the North Atlantic Ocean. At this point, it is not clear whether the source of the noise is inherent in the TAGA and whether the noise can be significantly reduced. The presence of noise in the TAGA time series does not necessarily make the instrument unusable for making direct measurements of turbulent fluxes. However, flight patterns would have to be modified and sampling paths lengthened to overcome the effect of noise in the calculations. During FY 1994, a concerted effort will be made to precisely define the high-frequency characteristics of the TAGA.

The chemical modeling activities within the ACP during FY 1993 have been performed entirely in support of the 1-month field campaign. Initially, chemical box model studies were carried out to assist in the interpretation and analysis of the gas-phase chemical measurements made over the North Atlantic Ocean. Primarily, the box model studies were used to discount several photochemically based hypotheses that were put forward to explain the pollutant layering phenomenon observed during the field study. Additionally, the box model simulations were used to confirm the internal consistency of the gas-phase chemical measurements made during the campaign.

Further model simulations have been performed with a one-dimensional version of a comprehensive photochemical model based on the STEM-II model of Carmichael et al. (1991). These simulations were performed to explore other possible physical mechanisms for the origin of vertical pollutant layering. These mechanisms were primarily concerned with one-dimensional boundary layer and dry deposition

processes and their roles in stratifying pollutant profiles. Analysis of these simulations is continuing; however, initial results indicate that the combination of photochemistry and simple one-dimensional boundary layer processes cannot fully account for the profiles observed over the North Atlantic Ocean in FY 1992.

Other modeling activities within the ACP included the implementation and testing of a comprehensive, super-regional-scale chemical model, based on the STEM-II regional-scale model of Carmichael et al. (1991). This model, STEMG, has been designed to perform three-dimensional chemical model simulations over continental-sized domains. Plans were formulated to use the model to simulate the August-September 1992 time period over a domain encompassing eastern North America and the North Atlantic Ocean. Meteorological and emissions data for these simulations are being prepared.

Several related modeling studies were also carried out during FY 1993. PNL staff have prepared a paper (to be published in FY 1994) that gives an overview of the state of regional-scale modeling. This paper presents limitations on comprehensive tropospheric chemistry/transport models within the context of a set of issues currently facing the environmental scientific and policy-making communities. A number of improvements are discussed in a prioritized manner including feedback processes between meteorology and chemistry; aerosol formation in cloud development with subsequent effects on wet removal, dry deposition, and surface exchange processes; and impacts of chemical perturbations on radiation, climate, and weather.

PNL scientists worked with staff at Brookhaven National Laboratory to use meteorological fields from the European Centre for Medium-Range Weather Forecasts to drive a modified version of the PNL global chemistry model (Luecken et al. 1991) applied to the atmospheric sulfur cycle. The resulting sulfate fields were used to calculate aerosol optical depths, which in

turn were compared to estimates of aerosol optical depth, based on satellite observations from the NOAA-9 Advanced Very High Resolution Radiometer (Wagener et al. 1994). The motivation of this work is to define confidence bounds for models describing the spatial, temporal, and physicochemical variations of aerosols prior to their use for scientific or policy-related purposes. It has been postulated that scattering of sunlight by anthropogenic aerosols can significantly reduce the amount of solar energy absorbed by the climate system. Although the results must be regarded as preliminary, they demonstrated a general correspondence between simulations and observations in regions contaminated by anthropogenic sulfur aerosol. Biases evident in other regions could be explained in terms of either aerosols not considered in the simulation or potentially correctable deficiencies in the sulfur model.

#### **Goals for FY 1994**

The major effort planned for FY 1994 is to complete the analysis of data collected during the FY 1992 and FY 1993 field campaigns. Modeling work, using the STEMG code, will form the center of this analysis, with continued empirical studies as presented in Berkowitz et al. (1993). Completion of manuscripts in progress will be the focus of this effort, as this program is brought to completion at the end of FY 1994.

A hypothesis is being investigated that relates subsidence from anticyclonic surface circulations to the elevated mixing ratios of ozone that were observed aloft above the marine boundary layer during the FY 1992 and FY 1993 field campaigns. We will use a one-dimensional boundary layer model used in conjunction with a simple ozone photochemistry scheme to test this theory. Analyses of measurements taken from PNL's G-1 aircraft would form the basis for the initial conditions for the modeling study.

A second hypothesis to be investigated suggests that a corridor for pollutant transport from

North America to Europe may exist at northern latitudes. Data to test this hypothesis were collected during FY 1993 and will be evaluated during FY 1994.

A primary focus of the analysis of the FY 1992 and FY 1993 field campaign data will be the use of the three-dimensional version of STEMG. Simulations will be performed for time periods covering both the FY 1992 and FY 1993 field campaigns over the western North Atlantic Ocean. Initial simulations will employ meteorological data obtained from NOAA's medium-range forecast synoptic analysis system for August and September 1992. These simulations will be performed using a relatively coarse grid resolution and will serve to complete the development of the STEMG model for field study support. Fine-grid production simulations for the western North Atlantic Ocean for both FY 1992 and FY 1993 will be performed using meteorological data obtained from the European Centre for Medium-Range Weather Forecasts. The purposes of these simulations will be three fold: 1) to identify and characterize the origin of the highest pollutant concentrations observed during the FY 1992 and FY 1993 field campaigns, 2) to estimate the potential for long-range transport of photochemical pollutants from North America to Europe, and 3) to further explore possible mechanisms for the observed pollutant layering.

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## Research Aircraft Operations

**Principal Investigator:** K. M. Busness

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

To fulfill a number of important national and DOE goals related to understanding the transport and transformation of energy-related pollutants and their impact on global climate issues, PNL operates a Gulfstream I (G-1) aircraft to obtain diagnostic environmental measurements aloft. The G-1 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 DOE's information needs related to National Energy Policy Act of 1992, and, more specifically, to supporting objectives of the Atmospheric Chemistry Program (ACP).

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### **FY 1993 Activities**

In August and September 1993, the G-1 aircraft was deployed to the western North Atlantic Ocean to participate in DOE's ACP field study conducted collaboratively with other participants in the multiagency North Atlantic Regional Experiment. Fourteen flights were conducted in support of ACP objectives (described elsewhere in this report) from a base of operations located at Halifax, Nova Scotia. In the FY 1993 field study, funding for aircraft hours was provided from the Research Aircraft Operations Program rather than from PNL's ACP (Continental and Oceanic Fate of Pollutants). This was part of a transition to the operational concept to be used in the future, and is discussed in Future Requirements/Applications.

A number of new equipment acquisitions/installations/applications to enhance airborne measurements have occurred or are currently under way. These include the following:

- improved dew-point system
- two-dimensional grey-scale optical particle probe

- fast-response absolute humidity hygrometer
- infrared surface temperature pyrometers
- ultrafine particle condensation nucleus counter
- development of an onboard 220-VAC power system
- enhancements to the aircraft's data acquisition system to improve speed and data-recording capacity and to provide data anti-aliasing for high-speed data conversion.

### **Future Requirements/Applications**

A new concept for PNL aircraft operations is being implemented to enhance access to the aircraft by the DOE atmospheric research community and to more effectively use aircraft and equipment resources. In FY 1995, the G-1 aircraft and associated measurement instrumentation will be operated as a DOE "Research Aircraft Facility" that will be made available to ACP researchers who require its use. The Research Aircraft Facility will consist of the G-1 aircraft,

numerous onboard airborne measurement instruments, a flight crew, and technical support personnel for installations, field operations, and in-field/post-field data processing.

As outlined in the 1993 ACP Program Announcement (DOE 1993a), approximately 250 h of G-1 aircraft time will be made available annually, funded separately from within ACP rather than from specific projects. The DOE will review technical feasibility and award flight time for proposals requiring use of the aircraft. Proposals will be submitted a minimum of 1 year in advance of expected aircraft use to allow effective coordination and scheduling of aircraft and equipment by the Research Aircraft Facility. It is expected that the G-1 aircraft will operate in each of the suggested field campaigns described in the ACP Program Announcement. It is also anticipated that collaborative aircraft measurements by potential users will be coordinated within those major campaigns, though specific, single-purpose uses will also be possible.

In addition to suggested field measurement campaigns listed in the ACP's Program Operation Plan (DOE 1993b) to be conducted in the coastal eastern Pacific (1994-1995) and the southwestern U.S. (1996-1997), it is anticipated that the G-1 aircraft will participate in a dedicated ultraviolet-B ozone study to be conducted in conjunction with the Atmospheric Radiation Measurement Program's Southern Great Plains test site. This will probably occur during FY 1996.

The acquisition and installation of an advanced satellite navigation system in the G-1 aircraft are expected in FY 1994. This system is a state-of-the-art Global Positioning System that

uses a multi-antenna array to determine aircraft attitude (azimuth, pitch, and roll angles), in addition to geographic position. The system, a Trimble Advanced Navigation Sensor Vector receiver, will replace an aging Inertial Navigation System currently installed in the G-1 aircraft. Relative to the Inertial Navigation System, the new system is approximately 25 times lighter in weight, requires approximately 10 times less space, and consumes approximately 60 times less power. The system will be used in conjunction with a gust probe to determine vertical/horizontal winds and to provide platform attitude data for corrections to radiation sensor measurements.

It is anticipated that researchers who are successful in acquiring aircraft hours will also bring other new instrument capabilities to the aircraft. However, it is important to continue to upgrade the measurement capabilities inherent to the Research Aircraft Facility and, insofar as is allowed by program and/or capital funding, to improve instrumentation for faster-response and higher-sensitivity measurements of various ambient species.

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## **ASCOT Program Scientific Direction**

**Principal Investigator: J. C. Doran**

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

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### **FY 1993 Accomplishments**

The principal activities for the fiscal year included the following:

- collaboration with European scientists
- meeting of ASCOT Science Team in February 1993
- establishing a Scientific Oversight Group to provide critiques of ASCOT activities
- preparation of a proposal solicitation for future ASCOT research
- presentation of an overview of the ASCOT program to a meeting of the American Nuclear Society
- planning for a modelers' workshop in November 1993
- support for meteorological measurements in the Front Range region of Colorado.

### **Collaboration with European Scientists**

In October 1993, Dr. Charles E. Elderkin presented a paper that describes ASCOT research in transport and dispersion in Colorado's Front Range at the Third International Workshop on Decision Making Support for Offsite Emergency Management, Schloss Elmau, Bavaria, Germany. In July 1993,

Dr. Elderkin traveled to Athens, Greece, to consult with Dr. John Bartzis at the National Center for Scientific Research. They discussed analyses of the meteorological and tracer data collected during a 1991 field experiment in Colorado's Front Range near DOE's Rocky Flats Plant. Also, Dr. Elderkin presented a paper in Athens that discusses the complex flow structures found near the Rocky Flats Plant.

### **ASCOT Science Team Meeting**

A meeting was organized for all ASCOT scientists in February 1993 in Salt Lake City, Utah. Participants presented results of their work in the previous year, including simulations of tracer dispersion near the Rocky Flats Plant in Colorado, measurements of complex layered flows from canyons near and downwind of the Rocky Flats Plant, four-dimensional data assimilation simulations of Front Range meteorology, simulations of thermally induced flows over idealized terrain landforms, and studies of regional drainage winds in Colorado and Washington. Plans were made for an extended experimental campaign in the Front Range during the summer and fall of 1993. The merits of various locations for radar wind profilers and sodars to be used during this period were debated and sites were identified.

### **Scientific Oversight Group**

Three scientists, two from universities and one from the private sector, were invited to

participate as members of a Scientific Oversight Group for the ASCOT program. The group attended the Science Team meeting and provided verbal and written feedback on their reactions to the meeting and suggestions for future activities. Based on their recommendations, it was decided that future funding of ASCOT research would be based on competitive proposals submitted by individual investigators. Additional recommendations were made for future comparisons of modeling results.

### **Proposal Solicitation**

Starting in FY 1995, funding of ASCOT research will be based on competitive proposals submitted by scientists from various federal laboratories. This marks a distinct change from previous practice, in which continued funding was not determined by external peer review of proposed work. A solicitation, describing the scope of the contemplated work, was prepared and distributed in June for comments. Funding will be divided between approved projects on the basis of peer-reviewed proposals and directed research activities, which are those activities necessary to maintain an infrastructure to support the program. Examples of the latter include the operation of remote-sensing instruments, such as radar profilers and sodars; the maintenance of a central data collection and distribution system; and program coordination.

### **Overview Presentation**

In September 1993, a paper was presented at a topical meeting of the American Nuclear Society in Charleston, South Carolina (Doran 1993). The meeting focused on environmental transport and dosimetry and featured a number of presentations by ASCOT scientists. An overview of the ASCOT activities relevant to this area of concern was delivered at the meeting.

### **Modelers' Workshop**

In response to another of the Scientific Oversight Group's suggestions, preparations were made for a modelers' workshop to be held in Santa Fe, New Mexico, in November 1993. Agreement was reached among potential participants concerning the set of simulations to be carried out. The results of several approaches to modeling dispersion processes will be presented and some comparisons will be made of the relative strengths and weaknesses of particular methods.

### **Support for Meteorological Measurements**

The National Oceanic and Atmospheric Administration's Environmental Technology Laboratory, formerly the Wave Propagation Laboratory, has maintained close ties with ASCOT over the last decade and more. To take advantage of the opportunities provided by their remote-sensing capabilities, funds were provided to the Environmental Technology Laboratory to operate three radar profilers and one radio acoustic sounding system in the mountains and plains to the north of the Rocky Flats Plant. These instruments formed an integral part of the field measurement campaign carried out in the region during August through October 1993. Data from the profiler array will be used to study the large-scale flow patterns affecting the meteorology of the area.

### **Future Activities**

Reviewers will be recruited to provide peer reviews of the research proposals, which were to be received by mid-October 1993. A further review will be provided by a panel convened in mid-December 1993, and the results will be used to help determine which proposals are to be funded for the period FY 1995 through FY 1997. In January 1994, an invited paper,

describing ASCOT's contributions to dispersion modeling, will be presented at an American Meteorological Society meeting. The annual meeting of the Science Team will be convened again in February 1994 in Salt Lake City. Discussion of future measurement campaigns in the Front Range region will begin at that time, as will discussions of possible future directions of the ASCOT Program. A report summarizing ASCOT activities in the 1991 field experiment in the Front Range region will be completed and published. Support may once again be provided for meteorological measurements in the Front Range; details will be determined after the Science Team meeting.

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# Atmospheric Diffusion in Complex Terrain

**Principal Investigators:** K. J. Allwine and J. M. Hubbe

The purposes of the Atmospheric Diffusion in Complex Terrain (ADICT) program are 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 the potential and actual environmental impacts arising from utilization 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- to global-scale models.

The objectives of the ADICT program include 1) the identification of the forcing mechanisms responsible for the observed wind, turbulence, and temperature structures in complex terrain; 2) the 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) the 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) the presentation of results at scientific meetings and in peer-reviewed journals.

The ADICT program maintains an integrated approach for accomplishing the research objectives, including field observations, data analysis, theoretical investigations, and numerical modeling. The research during FY 1993 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 contributed to understanding the interaction of ambient and locally generated wind systems and the effect on dispersion.

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## FY 1993 Accomplishments

The following outlines the specific objectives accomplished in FY 1993:

- Mathematical definitions of atmospheric stagnation, recirculation, and ventilation applicable to single-station wind measurements are described and investigated in a paper accepted for publication (Allwine and Whiteman 1993)
- Analyses continued on the meteorological data collected during the 1991 Atmospheric Studies in Complex Terrain (ASCOT) program's Front Range study. The influence on dispersion of canyon flows issuing onto the
- Rocky Flats Plant (RFP) site were investigated. Results were presented at two conferences (Hubbe and Allwine 1993a, 1993b).
- Research on identifying and characterizing the physical processes dominating dispersion in valleys was published (Allwine 1993); the paper gives results from the 1984 ASCOT Brush Creek valley experiment
- A valley atmospheric diffusion model, VALDRIFT, was developed jointly with the U.S. Forest Service. The model successfully simulated the continuous ground-level tracer plume from the 1984 ASCOT Brush Creek

valley tracer experiment. A description of the model is being prepared for publication.

- Under a joint effort with the other ASCOT programs, PNL participated in a fall 1993 meteorological study in the Front Range region. The regional flows and the canyon flows in the vicinity of Rocky Flats were studied with a network of remote-sensing instruments.
- Improvements were made to the PGEMS complex terrain dispersion model by allowing it to operate in a nested fashion. This enabled the terrain effects near the source to be resolved at a finer scale, while still maintaining a large enough domain for regional transport estimates, in addition to maintaining short computation times necessary for emergency response applications. The model will be applied to the Rocky Flats site.
- During June 1993, Dr. Rolland Hauser of California State University, Chico, California, began a year-long Associated Western Universities Northwest faculty appointment at PNL to collaborate with Drs. Allwine and Whiteman in their ASCOT programs. Dr. Hauser began investigating the variations in atmospheric turbulence levels as a function of landform type. Preliminary results were prepared for presentation at a 1994 conference.

### **Measures of Stagnation, Recirculation, and Ventilation**

Mathematical definitions of integral quantities used to characterize the stagnation, recirculation, and ventilation potential of various airsheds were developed. These integral quantities can be calculated from wind data collected at fixed-time intervals and at fixed heights in the atmosphere, and can be calculated, for example, from data from ground-based remote wind profilers.

These integral quantities, because they are calculated from data at single stations, provide useful characterizations of the flow at individual measurement points, but are true measures of the transport of a plume only under idealized homogeneous wind conditions.

The utility of these single-station measures for characterizing the air pollution transport potential of an airshed was investigated using 3 months of hourly surface and radar profiler measurements of horizontal wind speed and direction collected at three locations in the Colorado Plateaus Basin region of Arizona during the winter of 1990. A surface station located on a sheltered basin floor and exposed to diurnal wind systems experienced stagnations 62% of the time, recirculations 34% of the time, and ventilations 8% of the time; whereas, a surface station located on the south rim of the Grand Canyon and exposed to synoptic-scale wind systems experienced stagnations 8% of the time, recirculations 4% of the time, and ventilations 35% of the time. A radar profiler station, measuring winds to several hundred meters above the floor of the Grand Canyon, experienced stagnations approximately 20% of the time and recirculations approximately 25% of the time during the winter at heights up to ~400 m above the ground; above this height, to levels near 1100 m above the ground (the approximate height of surrounding plateaus), the frequency of stagnations and recirculations dropped rapidly, and the frequency of ventilations ranged from 40% to 70%.

### **Complex Flows in the Vicinity of Rocky Flats**

A network of towers and ground-based sodars, continuously operated by the ASCOT investigators since January 1991, was instrumental in identifying complex flow features in a very complicated terrain setting in the vicinity of the RFP near Boulder, Colorado. One feature identified was the influence of a cold-air jet issuing from a nearby canyon (the Coal Creek

canyon) in the Front Range onto the Rocky Flats bench and sweeping across the bench at various times throughout the night, influencing the winds (and thus the tracer concentrations) at the RFP. The second important feature was the layering of nighttime flows over the valley to the east of the RFP. This has the implication that the ground-level tracer released from the RFP became elevated as it traveled to the east away from the RFP. These flow phenomena can significantly influence the transport of released material from the RFP and, consequently, need to be identified for accurate assessments of the consequences of a release.

A meteorological field experiment was begun during July 1993, in collaboration with other ASCOT investigators, in which a network of sodars and radar profilers for measuring winds was installed for continuous operation in the Front Range area. Further investigations into the interactions of the various atmospheric scales of motion in the vicinity of Rocky Flats will be undertaken with this new data set.

### **Valley Dispersion Model**

A valley atmospheric transport and dispersion model, VALDRIFT, was tested using the tracer data from the 1984 ASCOT study in Brush Creek valley, Colorado. The results from simulations of tracer concentrations in Brush Creek valley compared quite well with the observed distribution from a tracer experiment. This model, though initially developed for the U.S. Forest Service to determine the extent of drift from aerial pesticide spraying activities, has a wide application for short-term prediction of atmospheric transport and dispersion in well-defined mountain valleys with relatively steep sidewalls. The model is phenomenological; that is, the dominant meteorological processes governing the behavior of the valley atmosphere are formulated explicitly in the model, albeit in a highly parameterized fashion. This model is

applicable under relatively cloud-free, undisturbed, synoptic conditions and is configured to operate through at least one diurnal cycle for a single valley.

The model computes the concentration fields for time-varying point and line sources located in a valley. The basic computational approach used in the model is to solve a one-dimensional (along-valley) species conservation equation for each of a number of "flowtubes" aligned along the valley axis. Lateral and vertical turbulent diffusion, variable emissions, deposition, and chemical transformations are treated as source/sink terms in the species conservation equation. In addition to conserving species mass within the flowtubes, the model also conserves total air mass, both for the along-valley flow in each flowtube and for the entire valley, using the air mass conservation equation. The valley is approximated by a series of cross sections in which the valley floor width, sidewall angles, elevation of the valley floor, and elevation of the ridgetops are specified.

### **Mesoscale Dispersion Model**

A mesoscale transport and diffusion model was tested for application to the tracer release during the 1991 ASCOT Front Range study. This model will be used to help identify and understand the dominant processes affecting dispersion in the vicinity of Rocky Flats. PGEMS is primarily for emergency response applications in regions of nonuniform terrain, is fully documented and operationally tested, runs on personal computers, and has been validated using tracer and meteorological data from experiments conducted in a complex terrain region near San Luis Obispo, California. A three-dimensional diagnostic wind model is used in PGEMS to specify the time- and space-varying winds over the modeling domain. A special feature of the wind model is that it accounts for flow channeling and blocking from

major terrain features during stable atmospheric conditions. PGEMS predicts ground-level concentrations and deposition fields of air contaminants released from point sources. Both wet and dry deposition and radioactive decay of the released material can be treated. A Lagrangian puff formulation is used to describe the concentration fields. PGEMS is applicable at source-to-receptor transport distances from a few hundred meters to a few hundred kilometers.

A three-dimensional wind model is used in PGEMS to specify the time- and space-varying winds over the modeling domain. The wind model is a diagnostic tool and uses upper air and surface meteorological data as input. Some dynamic effects are treated in a highly parameterized fashion in the flow model. For example, flow channeling and blocking from terrain features during stable atmospheric conditions are treated using the concept of a dividing streamline height. Nighttime drainage flows are also accounted for by specifying the surface winds as a function of terrain slope and orientation. The model can be run in a nested mode, allowing for finer resolution near the source while covering a broader region without exceeding typical memory and resources of personal computers.

### Future Studies

Analyses of the meteorological data collected during the fall 1993 Colorado Front Range experiment near the RFP will be performed to

help better understand the complex flows affecting dispersion around the RFP. In addition, the PGEMS mesoscale model will be applied to the tracer data from the 1991 Front Range study to assist in understanding the dominant processes affecting dispersion in the vicinity of the RFP.

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## Direct Simulation of Atmospheric Turbulence

**Principal Investigator:** 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. In addition, in cooperation with other PNL programs, the DSAT project jointly supports activities of DOE's Atmospheric Studies in Complex Terrain (ASCOT) program in experimental and analytical studies of atmospheric dynamics and their effects on diffusion of atmospheric pollutants.

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### **FY 1993 Accomplishments**

In FY 1993, the principal accomplishments of DSAT included the following:

- continued support of Mr. James C. Barnard's graduate research program in numerical simulations of stable turbulent boundary layer flows
- support (with one other ASCOT project) of a post-doctoral appointment for Dr. Shiyuan Zhong to work in the Boundary Layer Meteorology Group at PNL
- support (with two other ASCOT projects) for operation of two sodars and one 915-MHz radar wind profiler with a radio acoustic sounding system in the Front Range region of Colorado
- completion of an analysis and numerical simulation study (in cooperation with one other ASCOT project) of the interaction of valley and ambient winds in the Tennessee Valley and submission of a paper to the Journal of Applied Meteorology (Whiteman and Doran 1993)
- completion of an analysis and numerical simulation study of regional-scale drainage

flows in the Pacific Northwest and submission of a paper to the Monthly Weather Review (Doran and Zhong 1993).

### **Simulation of Turbulence in Stably Stratified Flows**

The DSAT project has been supporting Mr. Barnard's graduate research at the University of Washington aimed at understanding the turbulent dynamics of stable flows in the atmosphere. In FY 1993, a linear stability analysis of the stably stratified Ekman layer was performed that demonstrated that the vertical penetration of unstable motion increases as  $N$ , the Brunt-Väisälä frequency, increases. If this enhanced vertical penetration carries over to the fully turbulent flow regime, then for  $N$  greater than a certain critical value, stably stratified Ekman layers would become thicker than neutrally stratified Ekman layers. A direct numerical simulation of the turbulent flow will be performed to determine if such thickening occurs. If it is found, stable boundary layer theories may have to be extended to include this effect.

### **Post-Doctoral Support**

Dr. Zhong began a 1-year term on an Associated Western Universities Northwest post-doctoral appointment late in FY 1992. DSAT shared the cost of the first full year at PNL with

another ASCOT research project. In DSAT, Dr. Zhong carried out a series of numerical simulations with Colorado State University's Regional Atmospheric Modeling System on regional drainage winds in the Pacific Northwest.

### **Sodar and Profiler Operation**

The ASCOT program is currently focusing its attention on the Front Range region of Colorado, near DOE's Rocky Flats Plant (RFP). As part of the effort to assess the characteristics of drainage winds emanating from canyons in the Front Range west of the RFP, PNL operated two sodars near the mouth of Eldorado Canyon for a 3-month period spanning FY 1993 and FY 1994. Eldorado Canyon is a major canyon to the northwest of the RFP, and the objective of the study was to collect sufficient data to establish a local "climatology" of the winds in the area and to assess their impact on flows over the RFP. In addition, a 915-MHz profiler with radio acoustic sounding system was operated to the northeast of the RFP to obtain deep soundings of winds and temperatures that will help to define the ambient conditions under which canyon drainage winds develop. This effort was coordinated with other investigators from Los Alamos National Laboratory, Argonne National Laboratory, and National Oceanic and Atmospheric Administration's Environmental Technology Laboratory. DSAT supported this data-collection effort in cooperation with two other PNL ASCOT projects.

### **Analysis and Simulations of Tennessee Valley Winds**

This work was carried out jointly with another PNL ASCOT project, 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, and the numerical modeling was designed to test the

effects of the proposed mechanisms. Agreement between simulated and observed behavior was generally good, and the model results identified additional features that may also contribute to the observed behavior of the valley winds. A paper describing the results was completed and accepted for publication by the Journal of Applied Meteorology (Whiteman and Doran 1993).

### **Regional Drainage Flows in the Pacific Northwest**

A paper was completed that described a study of the development of "regional drainage flows" over the Pacific Northwest (Doran and Zhong 1993). During the late spring and summer months, strong winds from the northwest are often experienced over the Hanford Site. These winds may blow for a few hours or persist throughout the night. The winds are related to the presence of a deep marine layer to the west of the Cascade Range and strong heating to the east. Numerical simulations showed that the cooler air west of the Cascade Range is drawn over the crest by the thermal low that develops over the hotter eastern portion of the area. This air subsequently flows down the eastern slopes, where it is affected by local cooling, the Coriolis force, and terrain channeling to produce the characteristic winds found over the site.

### **Future Work**

FY 1994 will be the concluding year for DSAT. Support for Mr. Barnard's graduate program in the numerical simulation of turbulence in stably stratified flows will continue, and it is expected that his dissertation research will be essentially completed during this period.

Analysis of the profiler and sodar data collected near the RFP will be carried out. If new ASCOT funding is secured for future years, this analysis will form the first part of an extensive study of boundary layer structure and evolution in the region. If funding is not forthcoming,

efforts will be made to summarize the preliminary findings in the form of a journal article in FY 1994.

Numerical simulations will be carried out in two areas. In one, additional studies will be made of the properties of regional drainage winds in an effort to obtain a more general understanding of the phenomenon. In the second, numerical simulations of the relative contributions of slopes and valleys to drainage flows in the RFP area will be studied, using simplified topography based on the Front Range. These studies should help clarify the relative

roles that the local slopes and canyons play in producing the winds observed at the RFP.

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## **Interactions Between Surface-Exchange Processes and Atmospheric Circulations**

**Principal Investigator: W. J. Shaw**

The purpose of the Interactions Between Surface-Exchange Processes and Atmospheric Circulations (IBSEPAC) program is to improve the understanding of the interactions between surface fluxes of heat, momentum, and moisture and the structure of the atmospheric boundary layer. The general objectives of the program 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. Specific objectives for FY 1993 included the following: 1) continuing analysis of data collected during the FY 1992 field program, including an examination of techniques used to obtain heat and moisture fluxes over semiarid terrain; 2) validation of the newly acquired 915-MHz wind profiling radar using instrumentation mounted on the 122-m Hanford meteorological tower; and 3) procurement and testing of a laser scintillometer for improving the ability to measure area-integrated surface heat and momentum fluxes.

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### **FY 1993 Accomplishments**

The accomplishments of the IBSEPAC project in FY 1993 include:

- continued analysis of surface energy budgets for heterogeneous surfaces
- operation of a 915-MHz wind profiling radar with radio acoustic sounding system and evaluation of winds aloft against tower measurements
- support (with one other ASCOT project) of a post-doctoral appointment to Dr. Shiyuan Zhong.

### **Surface-Atmosphere Exchange Through a Semiarid Mixed Canopy**

A three-phase field experiment that investigated boundary layer fluxes over a mixed canopy was carried out on the Hanford Site during FY 1992. That experiment focused on defining the surface layer turbulence fluxes via the eddy-correlation technique and establishing the energy balance within the vegetation canopy. The experiment included twice-daily radiosonde profiles; continuous eddy-correlation measurements of momentum, heat, and water vapor fluxes; remote and in situ surface-energy-budget measurement; and plant and soil status measurements. During FY 1993, considerable effort was



devoted to analyzing these observations and preparing results for publication (Hubbe et al. 1994).

The suite of measurements was sufficient to calculate an energy budget for the heterogeneous surface that would balance the sensible and latent heat fluxes in the surface layer with the available energy at the surface. The available energy, measured at each of the component surfaces (bare soil, grass, and shrub), consisted of the net radiation at the surface minus the soil heat flux measured at 5 cm and the soil heat storage in the layer between the surface and the flux measurement level. In all cases, total surface layer heat flux was bracketed by the available energy for the three surfaces. The degree of budget closure depended on the values of fractional coverage used as weights in combining the available energies. Two sets of fractional coverage estimates were applied: one based on an in situ canopy-sampling technique and the other based on visual classification of a photographic image. In some cases, the combined available energy exceeded the surface layer heat flux during midday hours. Combined available energy, using in situ weighting and integrated over the daytime hours, exceeded the surface layer flux by 4% to 17%. Our achievement of good budget closure sets the stage for comparison of these observational data with various modeling approaches to the partitioning of energy at the surface.

### **Remote Sensing of the Lower Atmosphere**

In October 1992, PNL declared its trailer-mounted, 5-beam, 915-MHz wind profiling radar with radio acoustic sounding capability operational. This system is able to provide nearly continuous vector wind profiles to heights exceeding 6 km and hourly temperature profiles to heights as large as 1 km. Such a system is important to the objectives of the IBSEPAC program because it provides a means to at least partially measure the larger-scale circulations that interact with the surface fluxes.

The profiler was installed near the Hanford Meteorological Station (HMS) during the period November 1992 to January 1993. From February to April 1993, the system was run nearly continuously to evaluate its performance compared to instruments mounted on the 122-m HMS tower, which was located approximately 500 m away. The HMS tower has a standard set of regularly calibrated sensors for temperature, humidity, wind speed, and wind direction at multiple levels. In addition, an acoustic anemometer was mounted on the HMS tower to provide a measure of turbulent momentum flux. For the evaluation, the wind profiler was operated in a single high-resolution mode with a vertical resolution of 60 m. With this setting, the lowest range gate of the wind profiler corresponded to the highest measurement level on the tower. Results of that comparison showed that winds from the lowest levels of the radar's profile compared very well with winds measured on the tower. Comparison statistics for wind speed and wind direction showed a mean difference of  $-0.17 \text{ m s}^{-1}$  and  $-2.02 \text{ deg}$  and standard deviations of the differences of  $1.06 \text{ m s}^{-1}$  and  $21.7 \text{ deg}$ , respectively. Temperatures also compared well, with a mean difference of  $0.4^\circ\text{C}$  and a standard deviation of  $0.9^\circ\text{C}$ . It also appears from preliminary comparisons with acoustic anemometer data that it may be possible to obtain momentum flux profiles from this system. Unfortunately, relay failures in the radar prevented the testing of this possibility. The manufacturer has since repaired the relays, and additional data will be collected from the HMS tower to test the system's capability during FY 1994.

One of the fundamental questions remaining in boundary layer meteorology is how one determines a representative value of heat, moisture, and momentum exchange between the surface and the atmosphere when the surface has significant variations in temperature, moisture, or elevation. To assist in addressing this issue, the delivery of a laser scintillometer is expected in

FY 1994. This device is being manufactured for PNL by the National Oceanographic and Atmospheric Administration's Environmental Technology Laboratory in Boulder, Colorado. This remote-sensing system has the unique capability of measuring heat and momentum fluxes near the surface, averaged over a path as long as 600 m. This provides a significant new opportunity to assess how the fluxes from individual surface types combine to form a general flux over an area.

### **Post-Doctoral Support**

Dr. Shiyuan Zhong received her Ph.D. in meteorology from Iowa State University in the summer of 1992. She joined PNL as a post-doctoral associate through the Associated Western Universities Northwest in September 1992. The IBSEPAC program has shared the cost of her appointment with another DOE research project at PNL. Her appointment has been renewed for a second and final year, and she will continue to be partially supported by this project in FY 1994.

### **Goals for FY 1994**

Because of programmatic changes within DOE, FY 1994 will be the final year of the IBSEPAC program. The objectives for the final year are the following:

- complete the analysis of the FY 1992 field data and publish at least one peer-reviewed article describing the results
- complete the evaluation of surface modules used to represent surface-atmosphere exchange in heterogeneous terrain in the context of the IBSEPAC data and publish the results
- conclude the evaluation of the wind profiling radar, including an evaluation of its capabilities as a momentum flux profiling system and publish the results
- install and evaluate the laser scintillometer system so that it will be generally useful to a variety of DOE Atmospheric Studies in Complex Terrain (ASCOT) projects.

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## **Coupling/Decoupling of Synoptic and Valley Circulations**

**Principal Investigators:** C. D. Whiteman, M. Furger, R. K. Hauser, S. Zhong, and X. Bian

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

Current program goals are to gain a better understanding of the basic physics, driving forces, and interactions of thermally developed complex terrain circulations of different scales. These complicated interactions represent significant challenges that are being met with an integrated program of new field investigations, data analysis of past complex terrain experiments, and mathematical modeling of relevant physical mechanisms. Field investigations make use of remote and in situ atmospheric sounding devices, radiation and energy budget systems, tracer samplers, and basic meteorological sensors. Data sets come from DOE's 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 multilaboratory ASCOT program and is closely coordinated with two other ASCOT projects at PNL: the Atmospheric Diffusion in Complex Terrain (ADICT) and the Direct Simulation of Atmospheric Turbulence (DSAT) projects.

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### **FY 1993 Accomplishments**

The accomplishments of the DECUP research project for FY 1993 include:

- use of patterns in wind direction joint frequency distributions to analyze the coupling of valley wind systems with synoptic-scale flows.
- characterized air pollution dispersion meteorology with calculated stagnation and recirculation properties of the vector wind time series.
- demonstrating that sigma theta shows a distinct relationship to topographic setting.
- modeling investigations of basin-plains circulations.

- analysis of the uncertainties in atmospheric heat budgets calculated from data obtained by a network of wind profiling radars with radio acoustic sounding systems.
- operation of remote wind profiling equipment in the ASCOT intensive experiment in the vicinity of DOE's Rocky Flats Plant.
- partial support for Dr. Markus Furger, a visiting scientist from Switzerland's Paul Scherrer Institute.

### **Pressure-Driven Channeling in the Tennessee Valley**

A new climatological method for investigating the coupling and decoupling of valley and overlying synoptic-scale circulations was developed that relies on the recognition of patterns in wind

direction joint frequency distributions. This method was used with 5 years of twice-daily rawinsonde data and data from four 100-m towers in the Tennessee Valley to investigate the coupling between valley winds and the overlying synoptic-scale wind systems. Because of the moist climate of the Tennessee Valley, typical thermally driven valley wind systems, in which winds blow up the valley during daytime and down the valley during nighttime, are not strongly in evidence. Rather, winds in the Tennessee Valley are driven primarily by the along-valley component of the synoptic-scale pressure gradient. This finding has important implications for pollution transport and wind-direction forecasting. A journal article on this topic (Whiteman and Doran 1993) was completed and published in FY 1993.

### **Stagnations and Recirculations**

A new approach to defining critical air pollutant transport properties, such as stagnation and recirculation, has been developed in cooperation with the ADICT program. These transport properties were defined mathematically, and the numerical calculation of the properties from a time series of wind vectors was illustrated using wind data from towers and radar wind profilers located in a complex terrain region of the southwestern U.S. The method appears to be suitable for quantifying important aspects of the dispersion meteorology of a region. A journal article on this topic (Allwine and Whiteman 1994) was accepted and will appear in early 1994.

### **Dispersion Meteorology**

The standard deviation of wind direction, commonly called sigma theta, is related to horizontal turbulent diffusion in the atmosphere and has been widely used in dispersion calculations. An unusual set of new measurements of sigma theta has recently become available for an area of complex terrain in the Colorado Plateaus Basin in Arizona and Utah. This data set

includes wintertime data from 13 identical meteorological stations located in widely varying terrain throughout a large basin. Analyses of these data are under way as part of a joint effort with Drs. K. Jerry Allwine of PNL and Roland K. Hauser of California State University at Chico. Dr. Hauser is on sabbatical leave at PNL during parts of FY 1993 and FY 1994.

Initial analyses show distinct relationships between the elevation and exposure of the wind stations and the distributional statistics of the hourly sigma theta values. At ridgetop sites, hourly distributions have small standard deviations and positive kurtosis. Open-exposure sites that experience channeled flows show the greatest positive skewness and kurtosis. Sheltered-exposure and basin locations exhibit large standard deviations, smallest skewness, and negative kurtosis. Diurnal effects on wind-direction variability are most evident where local terrain contrast is most extreme and are difficult to detect, or are absent, at high-elevation ridgetop sites. There is a tendency for the product of the hourly sigma theta and the hour-average vector wind speed to yield a site-specific empirical constant, which exhibits a dependence on elevation, site exposure, stability, and strength of the overlying flow. The possibility that such relationships can be used to map the expected wind-direction variability in complex terrain is being investigated because this would make an important contribution to the understanding of turbulent dispersion of air pollutants in complex terrain areas. A presentation of the initial results of these analyses will be given at a national conference in early FY 1994.

### **Basin-Plain Circulations**

The Colorado State University Regional Atmospheric Modeling System (RAMS) has been used to conduct initial investigations of the large-scale circulations that form between basins and the surrounding plains. This work, which follows research conducted by two other investigators (Kimura and Kuwagata 1993), is expected

to provide an improved understanding of the effects of large-scale topographical circulations on the transport of air pollutants. The PNL simulations show that the plain-basin winds depend on mixed layer growth over the plain, the strength of upslope flows, and the topographic characteristics of the basin, as determined using the so-called topographic amplification factor (Whiteman 1990). The plain-basin wind can enter the basin abruptly in the early evening if the mixed layer over the plain grows deeper than the mountain height. A presentation on the results of several initial model simulations was made at the ASCOT Science Team Meeting in February 1993 (Whiteman and Zhong 1993), and a proposal to continue this research was prepared.

### **Atmospheric Energy Budgets Using Wind Profiler/Radio Acoustic Sounding System Networks**

The utility of networks of radar wind profilers and radio acoustic sounding systems (RASSes) for computing atmospheric heat budgets has been evaluated in a collaborative research project with Dr. Markus Furger of Switzerland's Paul Scherrer Institute and Dr. James Wilczak of the National Oceanic and Atmospheric Administration's (NOAA's) Environmental Technology Laboratory. Dr. Furger was a visiting scientist at PNL during parts of FY 1992 and FY 1993. Such heat budgets are useful in understanding the energetics of local flows and boundary layer processes. The work was jointly supported by DOE's ASCOT and Atmospheric Radiation Measurements (ARM) programs and was focused on the application of new remote wind- and temperature-sensing technologies for boundary layer meteorological investigations. The research involved the determination of the effects of typical wind and temperature measurement errors on the atmospheric heat budget equation using a Monte

Carlo-type model. The model was also applied to wind profiler/RASS data from the ASCOT/ARM/WISP (Winter Icing in Storms Program) experiment conducted in Colorado's Front Range region in 1991.

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

### **Front Range Studies**

Scientists in the DECUP program participated in the planning for a multilaboratory ASCOT-intensive experiment in Colorado's Front Range region during August through October 1993. A radar profiler/RASS, two Doppler sodars, and standard weather station equipment were deployed as part of this experiment. The continuous data stream from these instruments is being archived at Argonne National Laboratory. The 1993 ASCOT experiment was focused on dispersion meteorology in the vicinity of DOE's Rocky Flats Plant and was designed to investigate mountain-plain circulations and tributary flows at the mountain-plain interface. The time period of the mountain-plain circulation portion of this

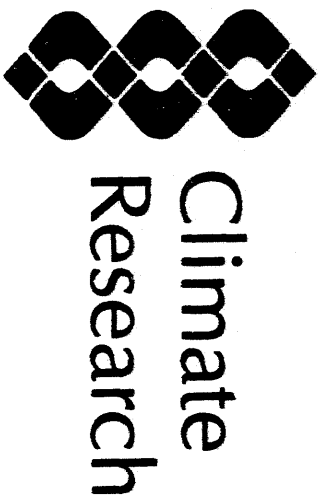
experiment has recently been extended to take advantage of opportunities to use related data sets being collected by NOAA.

### Future Research

In FY 1993, competitive ASCOT proposals were written in response to a DOE request for proposals for FY 1995 through FY 1997. Current ASCOT programs will end at the end of FY 1994, and future research will depend on the success of the new proposals.

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## **Climate Research**

Climate change research at PNL is aimed at reducing uncertainties in the fundamental processes that control climate systems that currently prevent accurate predictions of climate change and its effects. PNL is responsible for coordinating and integrating the field and laboratory measurement programs, modeling studies, and data analysis activities of the Atmospheric Radiation Measurements (ARM) Program. The ARM Program will increase the reliability of predicting regional and global changes in climate in response to increasing atmospheric concentrations of greenhouse gases, including carbon dioxides. 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 multilaboratory effort being led by PNL.

In FY 1993, PNL scientists conducted three research projects under the ARM Program. In the first of these projects, the sensitivity of GCM grid-averaged meteorological properties to subgrid-scale variations in surface fluxes and subgrid-scale circulation patterns is being tested in a single-column model. In addition, new procedures are being developed for extrapolating local point measurements of sensible and latent heat flux to GCM grid-averaged values. In the second project, a new and computationally efficient scheme has been developed for parameterizing stratus cloud microphysics in GCMs. With better estimation of critical microphysical properties, the optical properties of these clouds can be estimated more confidently. In the last project, a balloon-borne instrument package is being developed for making research-quality measurements of radiative flux divergence profiles in the lowest 1500 m of the Earth's atmosphere.

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

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

In FY 1993, ocean research related to climate change examined air-sea interaction processes, ocean mixed-layer dynamics, and the process of deep convection in the ocean. PNL is working to develop procedures for estimating air-sea gas transport from remote sensors and to improve parameterizations of the dynamics of the surface mixed layer, transport through the thermocline, and formation of deep water.

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

- Atmospheric Radiation Measurement (ARM) Program
- Point-Area Relationships for Global Climate Models
- A Stratiform Cloud Parameterization for General Circulation Models
- Photometric Studies of Clouds from an Atmospheric Radiation Measurement Site



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

**Principal Investigators: 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 of human activities on it. For instance, different energy scenarios can change the atmospheric concentration of carbon dioxide and the impact can be investigated through the use of GCMs. It is a DOE goal 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 the understanding of the physical processes modeled in GCMs that are most significant in limiting the model's performance.

The Atmospheric Radiation Measurement (ARM) Program is the major field measurements activity 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 currently represent the major sources of uncertainty in these models and are the issues identified by the Committee on Earth and Environmental Sciences of the Federal Coordinating Council for Science, Engineering, and Technology warranting the highest research priority.

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 research models. To address this objective, and other closely related 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 where existing capabilities are inadequate or nonexistent.

The design of CART incorporates the following elements:

- long-term 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
- network of surface meteorological observing stations at each of the sites to document surface meteorological and radiative homogeneity over an area comparable to the computational grid cell of a GCM
- 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

- acquisition of satellite data from existing operational and research satellites
- system to process and distribute data from the measurement sites and other sources to Science Team members
- archive to retain data and make them available to the general scientific community.

The ARM Program involves nine DOE national laboratories whose efforts are coordinated through the ARM Program Office at PNL. Participating institutes also currently include 17 universities, 9 government laboratories outside of DOE, foreign national investigators, and several domestic companies. Collaborative activities reach out and include an even larger group of participants.

### **FY 1993 Accomplishments**

In FY 1993, the ARM Program made substantial progress toward completing the establishment of its first site and the capability to routinely and automatically furnish quality data to members of the Science Team. A pilot measurement program in the tropical western Pacific Ocean provided valuable experience for deployment and operations in that area. Preparation and planning for deployment to both the tropical western Pacific Ocean and North Slope of Alaska sites continued, and plans began to be laid for future collaborations with national and international research efforts. Efforts during this fiscal year included the following:

- establishing the Central Facility and a number of extended facilities at the Southern Great Plains site
- continuing the development of the data acquisition and management system
- accessing data from national data sources, satellite programs, and other activities as required
- continuing to develop experiment designs and procedures to process and deliver data to the Science Team to meet their individual needs.

Key accomplishments included the following:

- completing the establishment of the Central Facility (shelters, utilities, instrument, instrument test pads, etc.) at the Southern Great Plains site, with the capability to accommodate planned and future instruments
- initiating routine electronic transmission of quality data sets to the Science Team in accordance with experiment designs and operational plans
- completion of the Pilot Radiation Observations Experiment (PROBE) at Kavieng New Ireland Province, Papua, New Guinea, in the tropical western Pacific Ocean as a collaborative effort with the World Climate Research Program's Tropical Ocean - Global Atmosphere (TOGA) Coordinated Ocean Atmosphere Response Experiment (COARE)
- establishment of agreements and procedures for routine electronic access to selected archives of the National Climatic Data Center and selected numerical and satellite data bases of the National Weather Service
- transition of the Atmospheric Emitted Radiance Interferometer (AERI), developed under

the Instrument Development Program, to operational testing at the Southern Great Plains site

- successful completion of intensive operational periods to support:
  - prototype testing of a cloud radar system under development as part of the Instrument Development Program
  - evaluation of a National Center for Atmospheric Research (NCAR)-developed four-dimensional data acquisition and assimilation system
  - collaborative efforts to evaluate the use of Global Positioning Satellite System signals to map precipitable water vapor in the atmosphere and to use high-resolution spectral imaging to map surface characteristics.

### **Experimental Approach**

The ARM program plan (DOE 1990) outlines the program's basic experimental approach. Field measurements will be used to initialize radiation and cloud process models and to provide 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, the

mean atmospheric properties of the encompassing atmospheric volume representative of a single column of a GCM grid cell, and 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 database 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 and deployment. The Southern Great Plains 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. Instrumentation and some other capital equipment for the tropical western Pacific Ocean will be acquired in FY 1994 for integration in FY 1995 into a facility designed for semiautonomous operation in remote locations.

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 remotely document, with higher time resolution, integrated columnar amounts of water vapor and liquid and vertical profiles of mean wind velocity components and temperature. Broad-band radiometers will observe

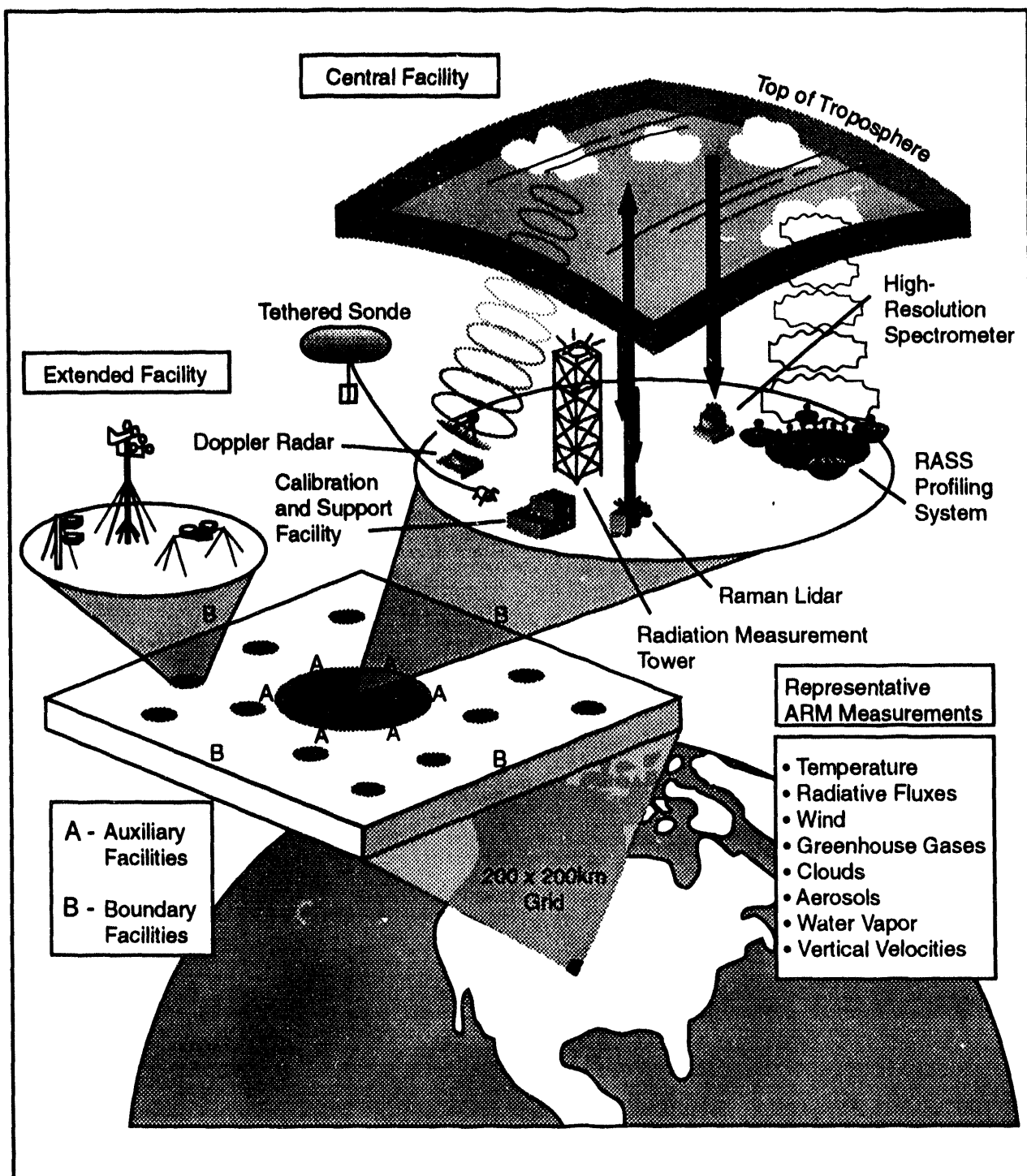


FIGURE 1. Conceptual Diagram of a CART Site

upwelling and downwelling radiation, as well as direct and diffuse solar radiation.

For the tropical western Pacific Ocean, the emphasis will initially be on observations of clouds and the impact of clouds and high water vapor concentrations on radiative fluxes. Generally, the initial instrument suite will focus on vertical profiling of key atmospheric variables, temporal and spatial characteristics of clouds and cloud cover, and surface radiative fluxes. The initial instrument siting strategy will call for widely spaced, semiautonomous, island-based sites that are approximately representative of a scaled-down Central Facility in the context of the CART template described above for the Southern Great Plains site. Facilities representative of extended facilities may be deployed in later years, depending on the conclusions from the analysis of data from the initial suite of instruments.

Table 1 lists the instruments and the measurements to be made at each facility in the Southern Great Plains and the initial suite of instruments that is currently planned for the first remote site for the tropical western Pacific Ocean.

The Instrument Development Program provides for the development of observational capabilities where needed, but where none exists, or where current capability is inadequate to the measurement task. Table 2 includes a summary of the instrumentation development efforts that were under way at the beginning of FY 1993. Sufficient progress has been made on developing several systems to warrant procurement of field-engineered systems for use and evaluation at the Southern Great Plains site. The laser ceilometer was evaluated during the pilot field program in the tropical western Pacific Ocean in FY 1993, and the infrared interferometer was tested at the Southern Great Plains site. Operational units for both are scheduled for installation early in FY 1994. A research prototype 35- and 94-GHz cloud radar was deployed to the Southern Great Plains site for initial evaluation in the summer of

1993. Development and evaluation of the cloud radar and the Raman lidar have progressed sufficiently to warrant their operational evaluation at the Southern Great Plains site. Systems designed for field use are expected to be deployed for testing and evaluation late in FY 1994.

### **Locale Status**

In 1990, five primary locales were recommended (DOE 1991) for long-term occupation (7 to 10 years), based on an evaluation of climate regimes and phenomenology, as well as surface homogeneity on the scale of a few kilometers. By priority, these were the following:

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.

Four supplementary locales were recommended for shorter-term measurements or campaigns. These included the Sonoran Desert, the Amazon rainforest, the high-latitude marginal ice zone, and the complex coastal region of northwestern U.S. and southwestern Canada.

During FY 1993, the five permanent sites recommended were reviewed in the context of the experience and progress in developing the first site and the supporting data system. Budget projections suggested that five long-term measurement sites could not be supported. Consequently, sites 4 and 5 were moved to supplementary site status. The priority order of the first three sites was unchanged, and plans to conduct long-term measurements in these three are proceeding. Deployment of instruments and facilities to the Southern Great Plains site was initiated in FY 1992 and continued in FY 1993. It is expected that the Southern Great Plains site will be largely complete by mid-FY 1994. The subsequent sites will be established at intervals

**TABLE 1. Instruments by Measurement Facility**

Instrument	Measurement
<b>Central Facility</b>	
915-MHz radar wind profiler with remote acoustic sounding system (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
Infrared thermometer	Vertical infrared radiometer for detecting the presence of clouds in the field of the microwave water radiometer
Laser ceilometer	Cloud-base sensor for clouds below 4 km
Whole-sky imaging system	See Auxiliary Facilities below
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 broad-band solar and infrared fluxes at heights of 60 and 25 m
Calibration facilities	Absolute radiometer; comparison stand; laboratory components
Aerosol instruments	Nephelometer; ozone sensor; cloud condensation nuclei counter; aerosol filter pack system with two size cuts; filter sample system for optical absorption; optical particle counting systems
Instrument group identical to Extended Facilities instruments	See Extended Facilities below
<b>Auxiliary Facilities</b>	
Whole-sky imaging system	Two-color digital imaging of the cloud field within sight at illumination levels greater than a quarter moon; possible mapping of sky radiance
<b>Extended Facilities</b>	
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
Wide-band solar and infrared sensors; multifilter rotating downwelling shadowband radiometer	Normal incident pyranometer; precision spectral pyranometer; pyrgeometer; pyranometer and pyrgeometer for upwelling irradiance; solar spectral radio meter; upwelling and 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; liquid precipitation
<b>Boundary Facilities</b>	
Collocation with wind profilers (some with RASS)	Wind and temperature profiles (with profiler-RASS)
Balloon-borne sounding system	Wind speed, wind direction, temperature, and humidity profiles
Microwave water radiometer	See Central Facility above

**TABLE 2. Instrument Development Program**

Instrument	Measurement
Micropulse laser ceilometer	Cloud heights, including cirrus; aerosol backscatter in the atmospheric boundary layer (in operational testing)
Raman lidar	Vertical profiles of water vapor, aerosol, and ozone concentrations; detectable cloud properties
Infrared interferometer spectrometer	High-spectral-resolution infrared radiances at the surface; known as the Atmospheric Emitted Radiance Interferometer (AERI) (in operational testing); temperature profiles to moderate altitudes may be feasible
High-Resolution AERI	Known as AERI-X; expected field testing in FY 1994
Solar radiance transmittance interferometer	Known as SORTI; field application remains questionable - to be evaluated in FY 1994
35- and 94-GHz radar systems	Cloud properties (Prototype Cloud Profiling Radar System [CPRS] ready for initial test and evaluation)
Lidar systems	Aerosol and cloud properties (may be integrated with Raman lidar development)
Multifilter rotating shadowband radiometer	Filter-band diffuse and total short-wave radiometer; transitioned to operational use - some follow-on development activity
Multichannel microwave water radiometer	Vertical profiles of water vapor
Dial lidar	Water vapor and trace gases - a feasibility study
Tethered balloon with stabilized radiometers	Short-wave radiative fluxes above the ground - prototype developed

of 24 to 30 months. Although the priority was based partly on the GCM parameterizations to be addressed, each locale was evaluated for the specific scientific questions to be addressed there, the data required to address those questions, and the feasibility of long-term support of a measurement site. Ocean-based measurements will be particularly challenging and possibly require innovative technological and measurement 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 that involve 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. The siting strategy to address the key questions in the tropical western Pacific Ocean is being assessed for deployment decisions. Instrument procurement and facilities development will begin in FY 1994, with initial deployment expected late in FY 1995.

In the North Slope of Alaska locale, environmental concerns about wetlands and wildlife are being examined in collaboration with state and local agencies. Siting strategies are being developed for further evaluation. Specific siting decisions are expected to be made several years prior to deployment, which is currently expected for FY 1996 through FY 1997. A collaborative effort in conjunction with the Arctic System

Sciences program, SHEBA (Surface Heat Budget of the Arctic Ocean), is possible. 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.

At each of these sites, calibration of all instruments, but particularly the radiometric instruments, will be a challenge. At the Southern Great Plains site, routine maintenance and calibration checks will be done by site operations personnel. For periodic recalibration, some of the instrumentation will be sent offsite (e.g., the Bowen ratio stations will be returned to the vendor once a year, while the radiometric instrumentation will be calibrated through standard intercomparison practices at a calibration facility set up at the site specifically for this task). The calibration facility for the Southern Great Plains site is being designed in accordance with a calibration plan that is in the process of being reviewed and revised. Some instrumentation has been procured for the calibration facility and some is on order. The calibration facility is expected to be operational during FY 1994.

### **Southern Great Plains Site Progress**

The phased occupation of the Southern Great Plains site continued in FY 1993, with the Central Facility's physical elements (trailers, tower, instrument sites, utilities, etc.) almost completed in the first half of the year, and additional instrumentation added in the latter half of the year. Instrumentation for most of the planned Extended and Boundary Facilities was ordered, with instruments installed and operating at nine Extended Facilities by the end of the fiscal year. Boundary Facilities were designed for implementation early in FY 1994. Twenty-five Extended Facilities and three Boundary Facilities are planned.

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 is close to the center of the Wind Profiler Demonstration Network, while the Boundary Sites are being located to complement the measurements of other wind profilers. Data from the Wind Profiler Demonstration Network are acquired through the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center in Asheville, North Carolina.

Other synergistic opportunities complement 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. Data from the Oklahoma Mesonet, a statewide system of surface meteorological instruments being installed by the Oklahoma Climate Survey, will be acquired and merged into the ARM data stream, supplementing data from the ARM Extended Facilities.

By the end of FY 1993, the following instruments were in place at the Central Facility (Figure 3):

- meteorological observation station
- CLASS-type balloon sounding system
- microwave water radiometer
- laser ceilometer
- rotating shadowband radiometer



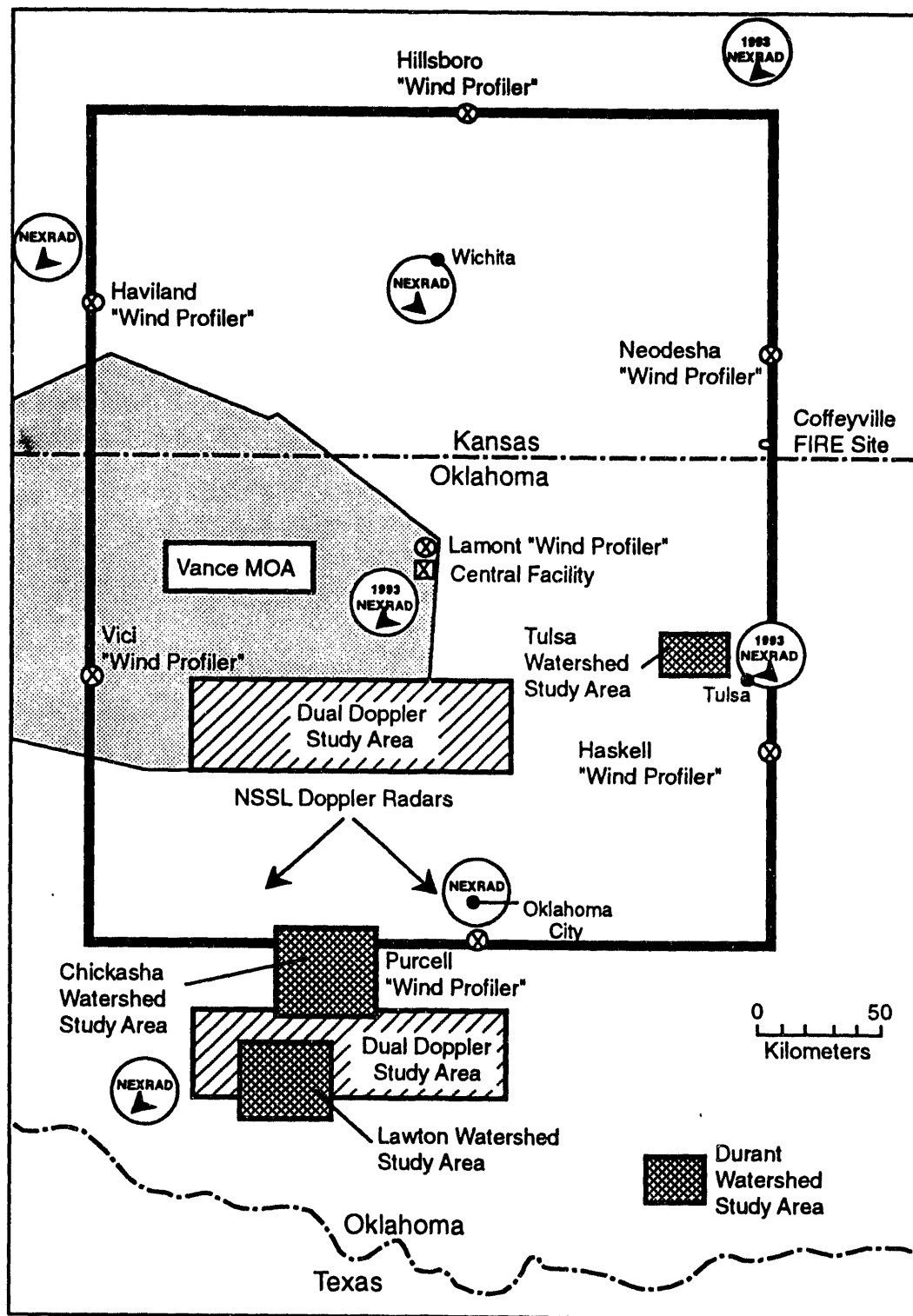


FIGURE 2. Southern Great Plains CART Site and External Data Sources

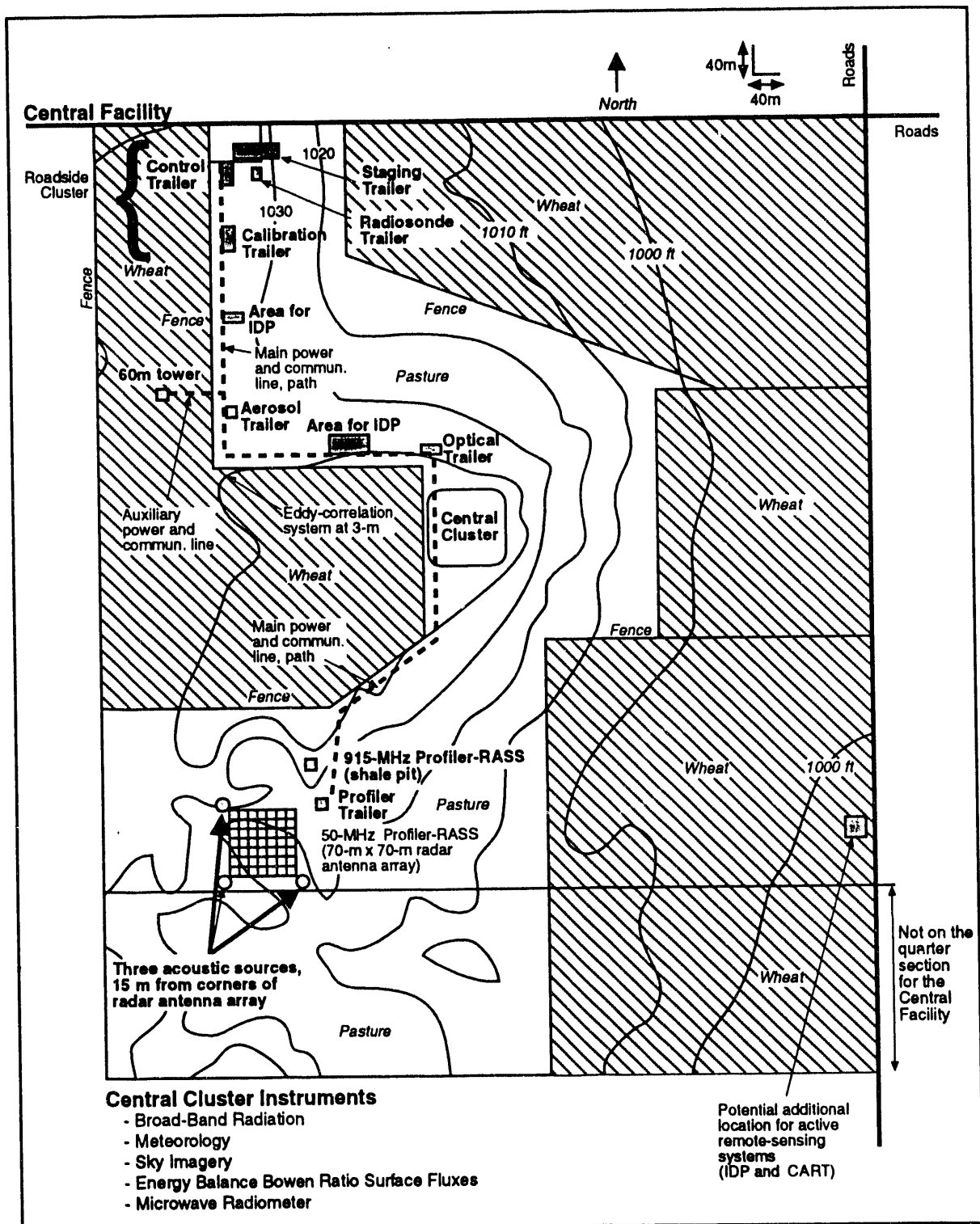


FIGURE 3. Schematic of Central Facility for Southern Great Plains CART Site

- AERI spectrometer (in testing)
- broad-band radiation sensors for downwelling radiation (pyranometer, pyrgeometer, and pyrliometer)
- energy balance Bowen ratio surface flux observation station
- 915-MHz wind profiler with radio acoustic sounding system (RASS)
- 60-m tower with meteorological instrumentation.

The 50-MHz wind profiler radar/RASS was partially installed, with an expected operational date in the first quarter of FY 1994. Additional instruments expected to be installed in early FY 1994 include a micropulse lidar (vertical), a digital whole-sky imager, and upwelling radiometers. The calibration facility is in the process of being designed, and implementation is expected to begin early in FY 1994.

The Site Data System routinely acquires data from the operational instruments and forwards quality-controlled data files to the experiment center at PNL. In the process, the site operator and site scientist routinely examine the data streams to ensure that the instruments are operational and behaving properly. Basic maximum-minimum and selfconsistency checks are performed automatically on each data stream by the Site Data System. Comments on site events and/or observations about instruments or quality of data are entered into the electronic site log by the site operator and the site scientist, and automatically by the Site Data System. Further quality control checks are performed at the experiment center before the data are delivered to the Science Team.

## **Tropical Western Pacific Ocean Preparations**

In preparation for the deployment of the second site to the tropical western Pacific Ocean, a program office for the site was established that involves the site program manager and several technical specialists, including oceanographic engineering. A primary effort of the site program manager and the site scientist has been to establish a siting strategy for the locale that addresses the key scientific issues in that locale. The recognition that the scientific issues encompass radiative forcing by clouds, particularly cirrus generated by deep convection, the radiative impact of high concentrations of water vapor, and the interactions between the tropical ocean with its high temperatures and the atmosphere led to the following requirements:

- continuous, basic observations of radiation and cloud properties over a broad spatial domain
- detailed, but not necessarily continuous, observations of atmospheric structure and properties
- observations of surface fluxes, boundary layer properties, and cloud structure in a purely oceanic environment.

The collaborative field program, PROBE, was initiated during the past fiscal year. PROBE was conducted from November 1992 through February 1993 at Kavieng, New Guinea, as an integral part of TOGA-COARE. ARM's purpose for PROBE was to conduct a pilot study of clouds and radiation in advance of ARM's establishment of long-term measurement sites in the tropical western Pacific Ocean. The contribution to TOGA-COARE was the establishment and

operation of an entire instrument site, as well as providing TOGA-COARE with surface radiometric data that were recognized shortfalls of the COARE experimental design. PROBE was highly successful in providing more extensive data of this type than ever obtained in the region. Additionally, it was a learning experience for ARM with regard to instrument performance and logistical issues in the tropical environment. Papers on PROBE will be presented at the upcoming American Meteorological Society meeting in Nashville, Tennessee, and an AMS Bulletin article is being prepared.

At the heart of the siting strategy being developed for the tropical western Pacific Ocean is the Atmospheric Radiation and Cloud Station (ARCS) concept, the product of an analysis of the most demanding scientific issues and the lessons learned during PROBE. ARCS is being designed to collect cloud and radiation data at several locations semiautonomously in the tropical western Pacific Ocean. If successful, ARCS may also be used at other CART sites. ARCS will be a fully integrated system of instruments, data management, and communications capable of operation in isolated locations for long periods of time. The first ARCS is planned to be located on Manus Island in Papua, New Guinea, and should begin collecting data in 1995.

A Technical Advisory Panel has been formed to review and comment on plans and activities for the tropical western Pacific Ocean. The panel draws on the experience of the TOGA-COARE International Program Office, field experience with instrumentation from several national centers, Australian representation from operational and research centers in the Bureau of Meteorology, and from the University of the South Pacific at Fiji. Considering the unique environmental and political needs of the tropical western Pacific Ocean locale, this panel will be a significant contributor to the success of this site.

## **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. As described previously, the scientific issues facing the ARM Program can be stated in the context of three broad topics: radiative energy transport; cloud formation, maintenance, and dissipation; and resolution limits important to representing atmospheric processes in GCMs and related models.

Within these broad contexts, as summarized in Stokes and Schwartz (1993), Science Team research generally falls into one of three related 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; and 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.

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 in six specific wavebands using the shadowband radiometer and

the temperature profile inferred from the profile of atmospheric-emitted radiation.

Intensive operational periods (IOPs) are planned to meet the data requirements of the Science Team experiment designs that cannot be satisfied by routine site observations. Two IOPs during FY 1993 were conducted to evaluate the performance of four-dimensional data assimilation under dynamic and thermodynamic conditions typical of the continental warm and cold seasons. Four-dimensional data assimilation is a technique in which sparse (temporally and/or spatially) observational data are incorporated in a model in a fashion that allows the complete specification of the meteorological variables. In addition, methods to estimate atmospheric divergence and vorticity within the volume of the site were evaluated. The project included additional instrumentation (the Integrated Sounding System from NCAR near the Central Facility and a mesoscale atmospheric model developed in conjunction with Pennsylvania State University. The coupled system (Integrated Sounding System plus model) is termed the Integrated Data Assimilation and Sounding System and represents the culmination of the first 3 years of ARM-supported research and is a demonstration of the power and limitations of data assimilation methods and their applications.

Data quality is an area of extraordinary concern within the ARM Program. To ensure that data sent to the Science Team are of known quality, data quality assessment algorithms and models are being implemented for automated quality control and assessment. An instrument performance model, for instance, is used to monitor the performance of the microwave radiometer, and quality measurement experiments (QMEs) formalize the intercomparison of specific data streams to further understand the data and their quality. A QME is, for instance, intercomparing the moisture profiles of the microwave water radiometer and the balloon sounding, and a QME is being developed to

intercompare line-by-line radiative code predictions to measurements from the AERI spectrometer developed in the Instrument Development Program.

The data delivered to the Science Team are based on specific requirements, as described in an experiment operations plan. This plan is derived from the experiment design and is refined through discussions with individual Science Team members. In effect, these represent an agreement between the Science Team member and the ARM 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, if desired.

### **Data Management System Development**

As depicted in Figure 4, the data system is comprised of three major components: the Site Data System, the Experiment Center, and the ARM Data Archive Center. The Site Data System communicates and controls site instrumentation, ingests data, checks data quality and calibration, and transmits data to the ARM 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 ARM Data Archive receives data both from the Site Data System and the Experiment Center and serves as the long-term 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.

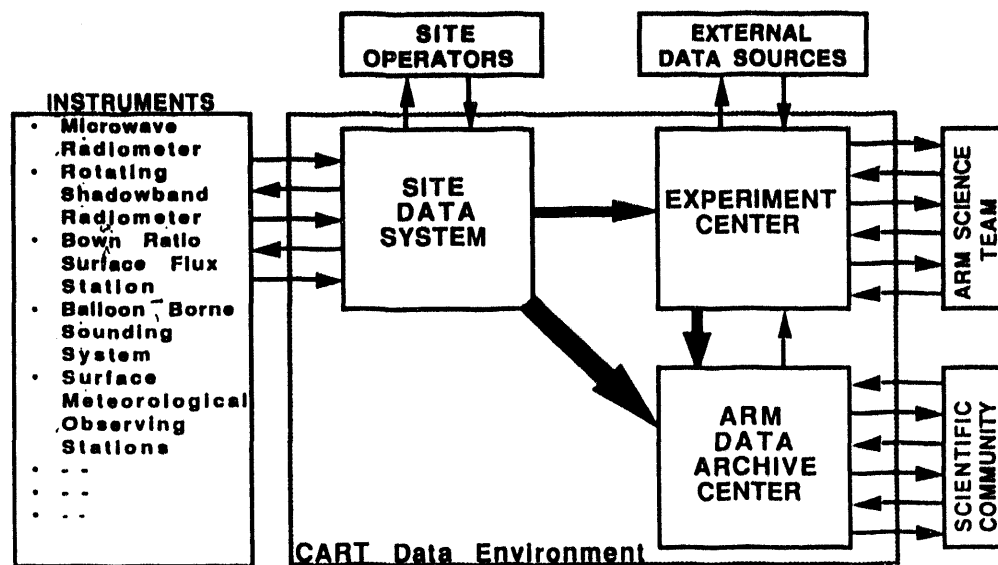


FIGURE 4. Schematic Representation of ARM Data System Components with Associated Data Flows

The software systems of both the Site Data System and the Experiment Center are based on the NCAR Zeb<sup>(a)</sup> software and are being developed by the ARM Program to be capable of ingesting, processing, displaying, and storing sizeable quantities of data in near real time. Early experience with Zeb indicated that, though designed with a field program like ARM in mind, it was inadequately designed to handle the volume of data required by ARM rapidly enough to permit real-time, continuous monitoring and quality control. Collaborative efforts with NCAR have rapidly produced dramatic improvements in Zeb's performance, and completion of this activity in FY 1994 is likely, though future sites may require additional developmental efforts.

(a) Zeb is a software system developed by NCAR to support field atmospheric research programs. Zeb is the basis for the implementation for the Site Data System and the Experiment Center. Zeb's modular architecture for data ingestion and processing makes the system expandable to handle virtually any instrument system or data type, to the limits of the host computer system.

The Site Data System was implemented with a dual capability. The "Production System" is the primary system for acquiring data from operational instruments, the site log, and other site data sources and for passing that data to the Experiment Center and the ARM Data Archive. The "Development System" is used to develop and evaluate 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 Site Data System is currently operational, with most of the desired automated procedures in place. Ingest modules for instruments brought on-line late in FY 1993 are still in development. Barring unexpected complications, the modules for these instruments, and for the new instruments being installed early in FY 1994, are expected to be completed in the second quarter of the fiscal year.

The Experiment Center is operational, but continues to operate largely in a manual mode. Automated data processing and quality control procedures require development and implementation. Significant components are the ingest

modules for accessing available external data, but an increased level of effort should provide this software early in FY 1994. National Weather Service gridded analyses from the nested grid model, surface weather data, rawinsonde data, aircraft data, and sounding data and imagery from geostationary and polar-orbiting satellites are acquired routinely with the cooperation of the National Meteorological Center. Special sensor microwave/imager data from the Defense Meteorological Satellite Program are expected to be received through NOAA's National Environmental Satellite Data Information Service. Early in FY 1994, it is also expected that data from the Forecast System Laboratory's Mesoscale Analyses and Prediction System model will be available through UNIDATA. ARM will act as a test bed for the UNIDATA efforts to develop a model product distribution system.

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. During the past year, DOE added to the list of people requiring support (i.e., Adjunct Science Team). Members of the Adjunct Science Team are scientists who are funded by other programs or agencies but who would benefit significantly by early access to ARM data and would, likewise, benefit ARM with products of their research. Additional Science Team members were added as the result of a DOE solicitation early in the fiscal year. By the end of FY 1993, the ARM Program enjoyed a Science Team membership of greater than 60, including three Adjunct Science Team members.

The ARM Data Archive continued to operate on an interim basis, pending the arrival of the first components of a new computer and data storage capability adequate for handling many data streams and users simultaneously. Until that new capability is developed, the ARM Data

Archive is acquiring and holding ARM data, but will continue to have a limited manual capability to retrieve and disseminate the data.

### **Collaborative Field Programs**

Limited pilot studies and IOPs conducted in cooperation with other programs have been valuable in evaluating the performance of instruments and investigating site operations concepts or plans. Pilot studies will continue as an approach to understand siting and site-specific instrument performance issues. IOPs represent another approach. IOPs at the Southern Great Plains site may involve programs or agencies outside of the ARM Program that have a potential to add significantly to ARM's research objectives or to contribute to meeting the operational and instrumentation needs of the program.

In FY 1993, one major field pilot study, PROBE, was undertaken in the tropical western Pacific Ocean. This effort, described previously, provided the ARM Program with an opportunity to gain operational experience in the tropical western Pacific Ocean and to evaluate some of the instruments that might be used there. Scientifically, analysis of the data acquired may well impact final decisions about instrument requirements and specifications. PROBE was highly successful on all accounts and has served its purpose of being an operational test bed.

Coordination activity for the North Slope focused attention on the need to be cautious about the impact of some instrumentation on wildlife and on the subsistence hunters on the North Slope. The major concern focuses on the sound source for the 915- and 449-MHz profiler radar/RASS systems that may ultimately be installed as part of the CART site. To investigate the potential impact, a sound source that mimics the RASSes was installed in an undeveloped area south of Point Barrow. The sound source will be operated for an extended period of time and will be monitored by state and local government

and wildlife management officials. Early results indicate little observable impact on wildlife behavior in the area. The time before deployment to the North Slope will be used also to evaluate instrument performance problems in the cold environment, knowledge that will aid in the development of specifications for instruments to be used there.

Two IOPs were defined in support of collaborating programs. The first was a cooperative effort with the University NAVSTAR Consortium (UNAVCO) and North Carolina State University (NCSU) to evaluate the use of radio signals from the Global Positioning Satellite System to infer the total precipitable water vapor in the atmospheric column over a wide area. Because water vapor profiles represent one of the greatest unmet measurement needs of the ARM Program, and one for which no adequate solution has yet been proposed, this effort may offer a benefit in addressing some aspect of this need. The UNAVCO/NCSU effort involved the installation of a receiving antenna on the roof of one of the site's trailers for a period of several weeks. Combined with other similar sites and the measurements from the CART site, investigators feel they acquired a data base that indicates some feasibility to the technique. Plans for future interaction are being discussed and may involve a long-term measurement period. If successful, ARM will benefit substantially from access to the acquired water vapor data.

The second collaborative effort involved the South Dakota School of Mines and the Jet Propulsion Laboratory, who proposed flying the National Aeronautics and Space Administration's (NASA's) ER-2 aircraft over the site at a 17-km altitude to acquire data using the Atmospheric Visible and Infrared Imaging Spectrometer (AVIRIS). AVIRIS uses 224 spectral channels from 0.4 to 2.45  $\mu\text{m}$  (in the visible and near-infrared spectrum) to make measurements of the vertical profile of water vapor and the bulk optical properties of atmospheric aerosols. The

Southern Great Plains site represents one of the best characterized regions of the atmosphere, permitting improved interpretation of surface imagery from AVIRIS. In support of the aircraft observations, two spectroradiometers were positioned at the Southern Great Plains site, along with several large black and white panels for the calibration of the airborne sensor. Data acquired from the flights and the spectroradiometers will be used with data from the ARM site in a variety of analyses and will provide an indication of the usefulness of this type of airborne instrumentation to the ARM Program. It is also evidence of NASA's interest in using the permanent ground site to provide a ground-truth point for the evaluation of airborne and satellite observations.

These collaborations are several examples where the Southern Great Plains site is fulfilling a need as a national user facility. Collaboration with other federal agencies involved in the U.S. Global Change Research Program, such as NASA, is one of DOE's goals for the ARM Program. Satellite measurements are of particular interest because they can be used to extend the limited area of highly resolved observations of an ARM site to larger regional and global applications.

### **External Program Coordination**

The ARM Program is one of several major research programs that address aspects of climate change, complementing 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 following:

- National Weather Service Modernization Program
- National Weather Research Program (commonly known as STORM)



- Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP)
- GEWEX Global Water Vapor Program (GVaP)
- Winter Icing and Storms Project
- Oklahoma Mesonet.

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

The GEWEX and the National Weather Research programs continue to be closely coupled with the objectives of the ARM Program. Collaboration with GEWEX will include participation in the GCIP scheduled for the Mississippi Basin and the GVaP, an intercomparison of water vapor measuring systems. ARM facilities may serve as a basis for the next field deployment of the International Satellite Land Surface Climatology Project. The Science Team, at its March 1993 meeting, agreed that the siting strategy for the North Slope should consider placing instrumentation out on the ice for at least part of the year. This strategy is compatible with the SHEBA program. A memorandum of participation is in place for GEWEX, and a similar memorandum will be established for SHEBA.

### **Future Research and System Development Activity**

The phased implementation of the Southern Great Plains site will be largely completed by the middle of FY 1994 with the installation of the last extended facilities and several auxiliary facilities from which whole-sky imagery can be

acquired. Some instrumentation remains to be designed, built, and/or procured. In particular, a Raman lidar will be procured and installed late in the year for cloud and aerosol measurement, a cloud radar will be acquired for permanent installation, and complementary airborne measurements are planned for initiation during the year. It is uncertain whether the lidar and radar will be installed and evaluated before the end of FY 1994.

The data system is largely in place and operating. Some experiment operations plans remain to be completed, and experiment designs and experiment operations plans for new Science Team members will be completed early in the fiscal year. With the new instrumentation being installed late in calendar year 1993, most Science Team members will be receiving their desired data by the second quarter of FY 1994. Efforts will continue to optimize the performance of the Zeb data-handling system at the site and in the Experiment Center. Data handling at the Experiment Center must be more fully automated than the current capability allows. System development will continue into FY 1994 and should be largely in place by the end of the fiscal year.

Assessments of the basic scientific questions facing each locale will continue. Analysis reports for the Southern Great Plains and the tropical western Pacific Ocean will be published and distributed in the second quarter of FY 1994. The siting strategy for the tropical western Pacific Ocean is largely established, but will be refined and more fully developed. Instrumentation for the tropical western Pacific Ocean will begin to be procured and modified for the expected operating environment and for semiautonomous operation; the ARCS and data management systems will be designed, but implementation will not begin before the end of FY 1994. The siting strategies for the North Slope site will be more fully developed and may change dramatically as more is inferred about the key scientific questions to be addressed. The

high-latitude performance of GCMs has just recently begun to receive much-needed attention from the scientific community, and the increasing level of activity is producing findings that could substantively change some of the existing concepts and perceptions relevant to a field program on the North Slope.

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## **Point-Area Relationships for Global Climate Models**

**Principal Investigator:** J. C. Doran

**Other Investigators:** C. D. Whiteman, K. J. Allwine, X. Bian, M. Furger, and J. Wilczak

The objective of the Point-Area Relationships for Global Climate Models project is to investigate the sensitivity of a single-column model to subgrid-scale variations of selected variables and to develop procedures for extrapolating local point measurements of sensible and latent heat fluxes at the surface to larger areas representative of a global climate model grid cell.

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### **FY 1993 Accomplishments**

In FY 1993, the principal activities of this project included the following:

- extensive analyses of the data collected in the 1992 Boardman, Oregon, field experiment
- presentation of results at conferences
- initial preparation of an article to be submitted to the Journal of Climate.

### **Data Analysis of 1992 Boardman Experiment**

Data collected during the 1992 Boardman experiment were reduced and extensively analyzed during this fiscal year. The Boardman area was characterized by two principal land types: dry sagebrush/grassland steppe and irrigated farmland. One of the principal findings was that the boundary layer's mean temperature structure showed fewer differences between the hot steppe area and the cool farm area than had been expected. This seems to be attributable to the effects of advection. As turbulent, well-mixed air blows from the steppe to the farm, the time scale for advection of air over the farm is less than the time needed for a significant decay

in turbulence and a resultant significant change in the temperature profile. Another interesting result was the identification of a "farm breeze" that was generated by the thermal forcing associated with adjacent warm and cool patches of land. The phenomenon is typically associated with significantly larger areas of warm and cool surfaces than those found at the Boardman site. The advective and farm breeze effects complicate efforts to develop effective parameterizations for subgrid-scale inhomogeneities in surface sensible heat fluxes. These phenomena are not treated in current climate models.

A model for estimating sensible and latent heat fluxes over agricultural crops was tested and refined using data from the Boardman experiment, and good results were obtained. Such a model should prove useful for extrapolating from point to area values of fluxes over the Southern Great Plains Clouds and Radiation Testbed (CART) site.

New algorithms for dealing with the data collected by the aircraft that flew during the 1991 and 1992 Boardman experiments were incorporated into several data processing codes. Efforts to understand the discrepancies between flux estimates from ground and aircraft instruments are continuing.

### **Surface Heat and Radiation Budgets**

As part of the Atmospheric Radiation Measurement (ARM) Boardman Regional Flux Experiment of 1991, a surface flux and atmospheric radiation measurement station was operated in the upper Columbia River Gorge near Boardman, Oregon. The experiment was conducted to investigate the effects of the spatial variability of sensible and latent heat fluxes on surface boundary layer properties (Doran et al. 1992) and to test different measurement systems that were being considered for use at the ARM CART sites. At the beginning of the experimental period, an equipment intercomparison sub-experiment was run to compare the Bowen ratio and eddy-correlation stations that would be used in the main experiment. Following this intercomparison, PNL's Bowen ratio station was deployed at the Krebs Ranch site, 27 km west-southwest of Boardman, Oregon, during the period June 2-27, 1991. In cooperation with DOE's Atmospheric Studies in Complex Terrain (ASCOT) program, this data set was processed and analyzed in FY 1993. The semiarid site had a Bowen ratio (ratio of sensible to latent heat flux) value of 5.0 during this period, and the equipment provided an unusually good set of radiation and surface heat flux data. A journal article documenting the surface and radiation budgets of this site is in preparation.

### **Atmospheric Heat Budgets from Ground-Based Remote Sensor Networks**

Radar wind profilers (WPs) and radio acoustic sounding systems (RASSes) are now available commercially and offer the promise of improving the knowledge of processes in the lower atmosphere that were until now unresolved spatially and/or temporally. The ARM program is evaluating a plan to install a network of 915-MHz boundary layer WPs/RASSes at the Southern Great Plains CART site. The new devices raise the prospect of gaining better insight into planetary boundary layer processes.

During FY 1993, Dr. Markus Furger of Switzerland's Paul Scherrer Institute visited PNL and, with Dr. James Wilczak of the National Oceanic and Atmospheric Administration's Wave Propagation Laboratory and Dr. C. David Whiteman of PNL, conducted a study of the feasibility of using networks of WPs/RASSes to compute boundary layer atmospheric heat budgets. This work was accomplished partly with funding from DOE's ASCOT program. The study, conducted using a Monte Carlo technique, investigated the effects of wind- and temperature-measurement errors on the uncertainties of individual terms in the atmospheric heat budget equation. The individual terms are not equally sensitive to measurement errors, and significant improvements in the evaluation of the heat budget equation would accrue from advances in temperature-measurement accuracy. Under favorable conditions, reasonably accurate estimates of each of the terms of the budget (except the radiation term) could be derived from measurements obtained from a triangular array of ground-based WPs/RASSes. The sensors provide nearly continuous measurements of the advection term so often neglected in atmospheric boundary layer studies. Summertime experiments seem more promising with respect to the height coverage of the RASS data because RASS measurements go higher in warm, humid air. Strongly baroclinic or divergent situations, however, produce significant uncertainties in the heat budget terms. The work was presented at the ARM Science Team Meeting (Furger and Whiteman 1993), and a journal article summarizing this work is in preparation.

### **Conference Presentations**

Results of ongoing research were presented at the Fourth Symposium on Global Change at Anaheim, California. An oral presentation (Doran et al. 1993) was given on the effects of heterogeneous distributions of surface heat fluxes on the properties of the atmospheric boundary

layer. A poster presentation (Crawford et al. 1993) described comparisons of flux measurements from towers and an aircraft.

### **Journal Article**

A major article summarizing some of the principal results of the 1992 Boardman experiment was begun. The article attempts to bring together data from a variety of instruments, including surface flux measurements, surface wind and temperature stations, airsondes, and sodars, to develop a picture of the response of the boundary layer to sharp contrasts in surface sensible heat fluxes and to examine the implications of that response for parameterization of such contrasts in climate models.

### **Future Work**

The paper describing the 1992 Boardman experiment will be completed early in FY 1994 and submitted for publication. Two papers will be presented at the Agricultural and Forest Meteorology conference in San Diego, California, in March 1994: one on a scaling analysis of the development of secondary circulations, such as farm breezes, and one on a numerical modeling analysis of the effects of advection on boundary layer structure over inhomogeneous surfaces. A more complete modeling analysis will be considered for another journal publication.

Attention will then shift to the Southern Great Plains CART site. It is expected that the various surface flux stations there will be coming on line relatively slowly and that the planned deployment of nearly 25 eddy-correlation and Bowen ratio stations will not actually be realized until late in FY 1994 or possibly even FY 1995. Accordingly, the development and preparation of required methodologies for extrapolating fluxes over the CART site will be the focus of the FY 1994 experimental part of the program.

Testing of surface-energy-exchange modules with available data will be begun, and initial effort to combine satellite information and model output from models, such as the Mesoscale Analysis and Prediction System (MAPS), will be made. Efforts will be started to develop statistical analysis tools that will provide estimates of the effects of partial cloud cover on the spatial distribution of surface heat and moisture fluxes. Systematic testing of the effects of the scale of surface inhomogeneities will begin in FY 1994, using a mesoscale model. Attempts will be made to summarize the results in terms of a characteristic length scale, or "patchiness," parameter that will indicate when the effects of subgrid-scale circulations are likely to become important. Initial development and testing of the protocols to be used for testing the sensitivity of a single-column model to the neglect of subgrid-scale processes will also begin in FY 1994. Trial runs will be made using data generated by a mesoscale model, which will provide input values for the single-column model.

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# A Stratiform Cloud Parameterization for General Circulation Models

**Principal Investigator:** S. J. Ghan

**Other Investigators:** L. R. Leung, R. C. Easter, J. E. Penner,<sup>(a)</sup> C. C. Chuang,<sup>(a)</sup> and J. McCaa<sup>(b)</sup>

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

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## FY 1993 Accomplishments

Progress was made in FY 1993 on the following project objectives:

- introduce cloud droplet number as a prognostic variable in the parameterization
- generalize a cloud droplet nucleation parameterization to treat multiple aerosol types
- further develop a column cloud model for evaluation of the parameterization at CART sites
- further develop the subgrid cloud parameterization
- evaluate the performance of the cloud parameterization in a GCM with prescribed cloud droplet number.

## Cloud Droplet Nucleation

The Colorado State University (CSU) bulk cloud microphysics parameterization (Cotton et al. 1986) was applied to PNL's GCM (an adaptation of the National Center for Atmospheric Research [NCAR] Community Climate Model [CCM]) in FY 1992. However, the CSU parameterization prescribes, rather than predicts, cloud droplet number and, hence, does not treat the influence of aerosols on clouds. If droplet number is to be introduced as a predicted variable in the GCM, a computationally efficient treatment of droplet nucleation must be developed. Such a treatment involves two tasks. First, the nucleation rate must be related to the number of aerosols activated as cloud condensation nuclei. Because most cloud droplets are formed when aerosols are activated near the cloud boundaries, we can express the droplet nucleation rate ( $NU_{vc}$ ) as

$$NU_{vc} = -\nabla \cdot NV$$

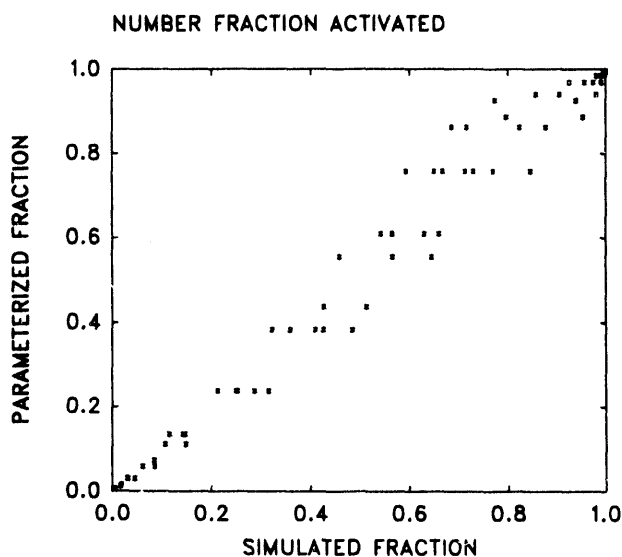
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(a) Lawrence Livermore National Laboratory, Livermore, California.

(b) University of Washington, Seattle, Washington.

where  $V$  is velocity and  $N$  is zero, except for inflow on the cloud boundaries when  $N$  equals the number concentration of aerosols activated. We have found that it is important to account for turbulent inflow, as well as explicitly resolved inflow, because mixing processes will otherwise destroy cloud droplets without forming new droplets. The treatment of turbulent inflow should be consistent with the parameterization of mixing to ensure that the predicted droplet number does not exceed the number concentration of aerosols activated as cloud condensation nuclei.

The second task in treating droplet nucleation is to parameterize the number of aerosols activated in terms of those variables that control the activation process. During FY 1992, a simple parameterization of the process was developed and a journal article was prepared (Ghan et al. 1993a). Figure 1 illustrates the performance of the parameterization compared with simulations by an explicit size-resolving aerosol activation



**FIGURE 1.** Comparison of Parameterized Number Fraction of Aerosols Activated with Number Fraction Simulated by a Size-Resolving Aerosol Activation Model, for Aerosol Number Concentrations Ranging from 50 to 500  $\text{cm}^{-3}$  and Updraft Velocities Ranging from 1 to 500  $\text{cm s}^{-1}$

model. The parameterization predicts the fraction of aerosols activated to within 30% of the detailed simulations, for aerosol number concentrations ranging from 50 to 5000  $\text{cm}^{-3}$  and updraft velocities ranging from 1 to 500  $\text{cm s}^{-1}$ . During FY 1993, the journal article was accepted for publication and a second was submitted (Ghan et al. 1993b) that generalizes the parameterization from a single aerosol type to multiple aerosol types.

### Column Cloud Model

An essential task in the development of the cloud parameterization is its verification. Although some aspects of verification will be achieved using climatological simulations with PNL's GCM, more control is possible by applying the cloud parameterization to forecast experiments in the field. This project will utilize 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 basic elements of the column model were constructed and used to develop the cloud microphysics parameterization (Ghan and Easter 1992). During FY 1993, the same parameterizations of cumulus convection and radiative transfer used in PNL's GCM were also applied to the column cloud model. A simplified treatment of the detrainment of condensed water from cloud tops was added to the cumulus scheme. Cloud radiative properties were expressed in terms of the simulated cloud water and cloud ice mass and number concentrations.

### Subgrid Cloud Parameterization

The coarse resolution of global models is clearly inadequate to resolve the climatically important features of most clouds and cloud systems. Subgrid variations in cloud properties



and cloud processes must, therefore, be represented in global models. During FY 1992, a statistical formalism was developed that expresses subgrid-scale variations in cloud microphysical properties in terms of idealized probability distributions. During FY 1993, the Mellor-Yamada second-order closure scheme was applied to the liquid-phase cloud variables in the column cloud model. Both variance and mean cloud water and rain are now predicted. By assuming idealized probability distributions for the cloud variables, the influence of subgrid cloud variations on cloud processes (autoconversion and collection) is represented. Joint probability distributions for cloud water and rain were introduced to treat the subgrid dependence of collection on cloud water and rain. The correlation between cloud water and rain is treated by assuming that most of the subgrid correlation is the result of differences between cloudy and clear air.

### **General Circulation Model**

The ultimate goal of this project is to improve the treatment of stratiform clouds in GCMs. To this end, during FY 1992 and FY 1993, the CSU bulk cloud microphysics parameterization was applied to PNL's GCM. Further, the approximations of Ghan and Easter (1992) were adopted to permit the use of much longer time steps, and it was found that microphysical time steps of 20 min are accurate, given the weak vertical velocities resolved by the GCM. Subgrid variations in clouds and cloud processes are not yet treated in the GCM. Also, a simple parameterization of the detrainment of condensed water from cumulus clouds was applied, the diurnal cycle of solar radiation was added, and the Biosphere-Atmosphere Transfer Scheme (Dickinson et al. 1993) was introduced to treat the diurnal storage of energy and moisture at the surface. One preliminary 30-day simulation with prescribed droplet number was performed, and it was found that, without any tuning, the simu-

lated global planetary radiation balance is within 10 W/m<sup>2</sup> of satellite observations for both solar and infrared radiation. Simulated cloud cover is high, approximately 80%, because the model simulates extensive ice clouds that are too thin to be observed. Supercooled cloud droplets are simulated at temperatures as low as -15°C. It was suspected that supercooled droplets are not simulated at colder temperatures because the explicitly resolved vertical velocities are weak and because the diffusive treatment of subgrid vertical transport is inappropriate for moist plumes.

During FY 1993, we also began to explore the prediction of cloud droplet number in the GCM. Some very short (24-h) simulations were performed with predicted droplet number, in which the droplet nucleation rate is expressed in terms of resolved and turbulent airflow into clouds, and a prescribed droplet number nucleated. The simulated droplet number varies from values much lower than the number nucleated (when collection processes deplete droplet number) to values up to but never exceeding the number nucleated (when collection processes are weak). This lays the foundation for application of the droplet nucleation parameterization (Ghan et al. 1993a, 1993b) once subgrid variations in vertical velocity have been parameterized.

### **Future Work**

The following tasks are planned for FY 1994:

- apply the cloud parameterization to NCAR's CCM2 and perform a 3-year simulation with prescribed droplet number; compare simulated cloud, precipitation, and radiation fields with surface and satellite observations
- complete the representation of subgrid variations in cloud microphysics; evaluate the impact of subgrid variability on the climatology simulated by the GCM

- apply the droplet nucleation parameterization to the GCM and evaluate for prescribed aerosol distribution; compare simulated and observed cloud droplet number, as well as other cloud-related fields
- evaluate the cloud parameterization when applied to ARM CART sites in a column model; 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 Site**

**Principal Investigators:** C. D. Whiteman, J. M. Alzheimer, G. A. Anderson, and W. J. Shaw

This project is developing a small tethered balloon sounding system to collect routine in situ vertical broad-band radiometric profiles through the Earth's atmospheric boundary layer. The profiles will be made to depths of up to 1500 m above ground level under cloudy and noncloudy conditions. The two major technical objectives of this project are to construct a stable self-leveling platform that can keep the radiometers horizontal, regardless of atmospheric turbulence, and to collect quality-controlled radiometric data with known and stated error bounds.

The project approach has been to develop a stabilized platform that is carried in a tether-line harness approximately 30 m below a small, helium-filled, blimp-shaped balloon. The platform is stabilized by an automatic control loop that, through the use of motors and gears, endeavors to keep the radiometers level despite turbulent motions and oscillations experienced by the balloon and tether line. The platform carries both upward- and downward-looking solar and total hemispherical radiometers. Measurements from these instruments allow downward and upward short-wave and long-wave components to be determined, as well as all-wave net radiation. A commercial atmospheric instrumentation package is carried on the balloon, so that balloon height, pressure, temperature, humidity, wind direction, and wind speed data are also collected for each sounding. The radiometric and platform attitude (azimuth and elevation angle) sensor data are processed and stored onboard using a small, lightweight, programmable data acquisition system. The meteorological data, on the other hand, are transmitted to the ground at 403 MHz and are available during the balloon profile so that the operator of the winch can monitor the developing meteorological conditions.

Efforts in FY 1993 were focused on flight tests designed to characterize the performance of the stabilization system, testing of a theoretical model that determines the radiometric errors associated with any residual tilt, reporting of the design and performance of the stabilization system, and preparation of a follow-on proposal for further development of the radiometric sounding system.

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### **FY 1993 Accomplishments**

Initial flight tests were conducted to measure the performance of the Sky Platform and the Motion Sensing Platform, a separate platform that directly measures the tether-line motions that must be damped by the Sky Platform's stabilization system. The flights were conducted in a moderately sheared wintertime boundary layer. For one flight, the automatic control loop stabilized the Sky Platform to within 0.8 deg. of horizontal, with oscillation standard deviations of approximately 2 deg. This performance, accord-

ing to a model that PNL developed to determine the radiometric errors associated with various tipping angles, is suitable for producing useful vertical radiometric profiles. Motion Sensing Platform data collected during a series of flights allowed the separation of angular and lateral accelerations, velocities, and displacements to characterize the tether-line motions. The Motion Sensing Platform, however, appears to have some internal vibration modes that differ from those of the Sky Platform.

A radiometric field experiment was conducted to test the performance of the theoretical model that PNL developed to calculate the radiometric measurement errors caused by a residual tilt of the Sky Platform. The radiometric data verified the model and confirmed the PNL original platform operating specifications.

A 3-year research proposal for further development and testing of the Sky Platform and Motion Sensing Platform and for radiometric research with this new tool at Cloud and Radiation Testbed sites was written in FY 1993. Research results were presented at two conferences (Alzheimer et al. 1993a, 1993b; Shaw and Whiteman 1993a, 1993b; Whiteman et al. 1993). The Sky Platform was demonstrated at one conference, and two journal articles are in preparation.

#### **FY 1994 Objectives**

Future work will involve the further testing and improvement of the Sky Platform stabilization system and the Motion Sensing Platform design and instrumentation, field tests of the operating limitations of the Sky Platform, testing of Sky Platform radiometers against standard radiometers, procurement and modification of a commercial tethered balloon system for operation at a Cloud and Radiation Testbed site, comparison of radiometric sounding data with radiative transfer models, and preparation of research papers.

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Shaw, W. J., and C. D. Whiteman. 1993a. "Accuracy of Radiation Profiles from a Self-Leveling Balloon-Borne Platform." *Preprints, Eighth Symposium on Meteorological Observations and Instrumentation*, January 17-22, 1993, Anaheim, California, pp. 121-126.

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## **Characterization of Cloud/Aerosol Interactions with Solar and Long-Wave Radiation**

**Principal Investigators:** N. S. Laulainen, J. J. Michalsky,<sup>(a)</sup> L. C. Harrison,<sup>(a)</sup> N. R. Larson, and J. L. Berndt

The purpose of the Quantitative Links component of DOE's Expanded Carbon Dioxide (CO<sub>2</sub>) 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<sub>2</sub> 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 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, with cloud structure and type, for a midlatitude continental area, a nine-station network (the Quantitative Links Network) was established in the midwestern and eastern United States. Each station is equipped with a uniquely designed multifilter rotating shadowband radiometer (MFRSR) to measure direct normal, diffuse horizontal, and global horizontal irradiance in six narrow-wavelength pass bands. An additional measurement in a broad pass band, covering a large portion of the short-wave spectrum, approximates total short-wave irradiance. Measurements of downwelling long-wave radiation are made with a pyrgeometer or precision infrared radiometer. 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 fourth year of a 5-year research period.

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## **FY 1993 Results**

Specific objectives accomplished during FY 1993 were 1) testing and calibration of the instrumentation; 2) operation and maintenance of the field sites, including the diagnosis and correction of malfunctions; 3) data collection and archival; 4) further development and application of data analysis techniques to interpret the measurements; and 5) 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**

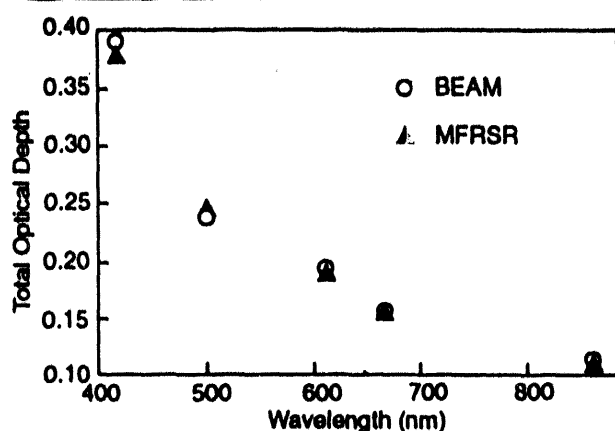
The primary instrument at each site is the MFRSR, developed jointly at PNL and SUNY-Albany. The instrument was described in a previous annual report (Laulainen et al. 1992) and only the essential features are presented here. The MFRSR measures total horizontal and diffuse horizontal irradiance in six narrow-wavelength pass bands and in one broad band that is used to measure total short-wave irradiance. Direct normal irradiance is calculated for each pass band by subtracting the diffuse irradiance from the total horizontal irradiance and dividing by the cosine of the solar-zenith angle. A microprocessor on the main circuit board controls the band motion, acquires data from the MFRSR and auxiliary instruments, and communicates via a modem. Data acquisition, processing, and analysis are performed on Sun SparcStation systems and graphics terminals, which are available both at PNL and SUNY-Albany.

During FY 1993, in a collaborative effort with the U.S. Department of Agriculture, broad-band measurements of ultraviolet-B (UV-B) radiation were added to three of the network sites. The additional measurement required a modification to the data acquisition system that resulted in increasing the number of available data channels from 16 to 32. This modification was

already planned for the Atmospheric Radiation Measurement (ARM) program to accommodate additional measurement requirements of the Solar and Infrared Observing System planned for deployment at the Southern Great Plains CART site in Oklahoma and Kansas. The Solar and Infrared Observing System consists of a suite of broad-band radiation instruments, the MFRSR, and a data logger. In addition, PNL and SUNY-Albany completed a licensing agreement in May 1993 with Yankee Environmental Systems, Inc., to produce and sell the MFRSR commercially.

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). With this response information, the direct normal irradiance component can be corrected. 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 a direct beam radiometer constructed from an MFRSR detector head, and that computed from the MFRSR-derived total and diffuse irradiance measurements. The results of these measurements made during late 1992 are displayed in Figure 1. The bias between the two instruments is smaller than or comparable to that expected from wavelength pass bands that are assumed to match to an accuracy of 1 nm. These results support the assertion that the cosine correction algorithm applied to the MFRSR observations does an excellent job of reproducing direct beam irradiance measurements. Further discussion may be found in Harrison et al. (1993).

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. Because optical depth retrieval via Langley regression is often



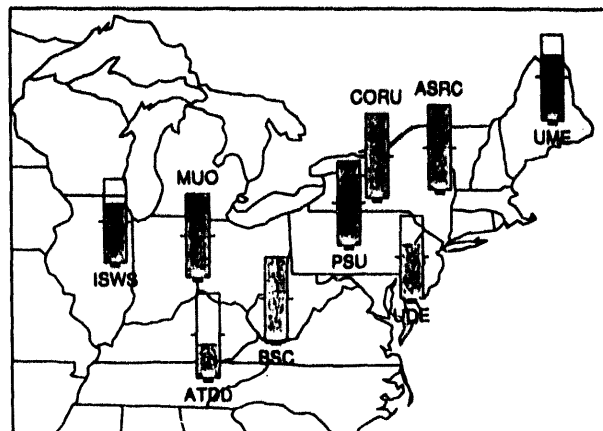
**FIGURE 1.** Comparison of Aerosol Optical Depths Derived from a Direct-Beam (DIRECT) MFRSR Module and MFRSR Observations Taken in Late 1992

complicated by cloud transits and other time-varying interferences, an objective algorithm for performing these regressions was also developed (Harrison and Michalsky 1993). This is an important capability if one wants to have a robust means for providing comparable optical depth retrievals from widely varying historical data and for supporting large networks of radiometers, such as the MFRSR.

### Site Operation and Maintenance

The installation of instruments at the nine sites of the Quantitative Links Network was completed in the fall of 1991. The nine sites selected are shown in Figure 2. A description of the sites may be found in a previous annual report (Laulainen et al. 1993). The Bondville, Howland, and Oak Ridge sites were selected for the installation of the UV-B sensors and the data system upgrade. Each site is visited at least annually for instrument calibration.

During FY 1993, the principal maintenance problem was caused by lightning strikes in the vicinity of the instruments. The most severe knocked out the Bondville and Oak Ridge units for several months. Spare electronics boards



**FIGURE 2.** Location of the Quantitative Links Network Sites with FY 1993 Bar Statistics on Data Retrieval Success Rate. Bars indicate data acquisition as a fraction of total number of days of deployment. ATDD = Oak Ridge, Tennessee, National Oceanic and Atmospheric Administration/Atmospheric Turbulence and Diffusion Division; ASRC = Albany, New York, Atmospheric Research Sciences Center; BSC = Bluefield, West Virginia, Bluefield State College; CORU = Ithaca, New York, Cornell University; ISWS = Bondville, Illinois, Illinois State Water Survey; MUO = Oxford, Ohio, Miami University of Ohio; PSU = Pine Grove Mills, Pennsylvania, Pennsylvania State University; UDE = Lewes, Delaware, University of Delaware; and UME = Howland, Maine, University of Maine.

from the three data system upgrades were available for replacing those damaged. In all, some eight incidents of lightning damage occurred.

### 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 Quantitative Links Network generates approximately 90,000 bytes of solar and atmospheric radiation and meteorological data each day. The data are transferred on nearly a daily basis from each of the nine 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 them. If any station 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 is arranged. The success rate for data capture during FY 1993 is represented in Figure 2 by the bar graphs for each station. As mentioned earlier, data loss resulted mainly from downtime caused by lightning strikes.

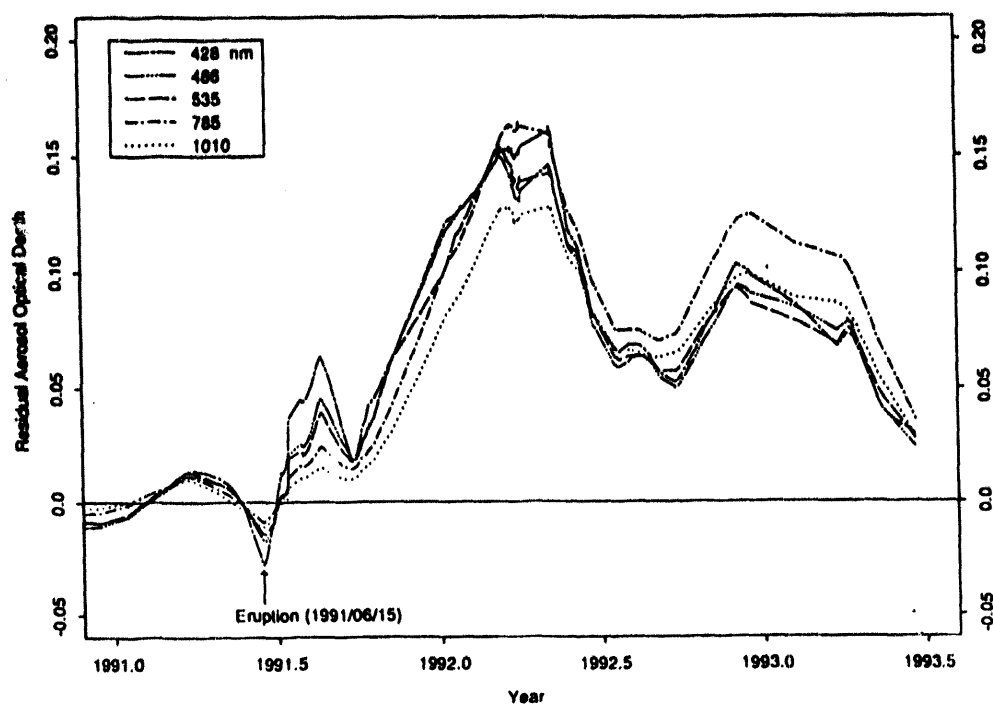
Software development efforts shifted to further development and application of data analysis software in FY 1993. An algorithm to perform the Langley method of atmospheric optical depth determination, including corrections for the cosine response of the MFRSRs, was implemented for the Quantitative Links Network, as well as for the Southern Great Plains site. The processed data files become the master data files to be used by the project and other 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

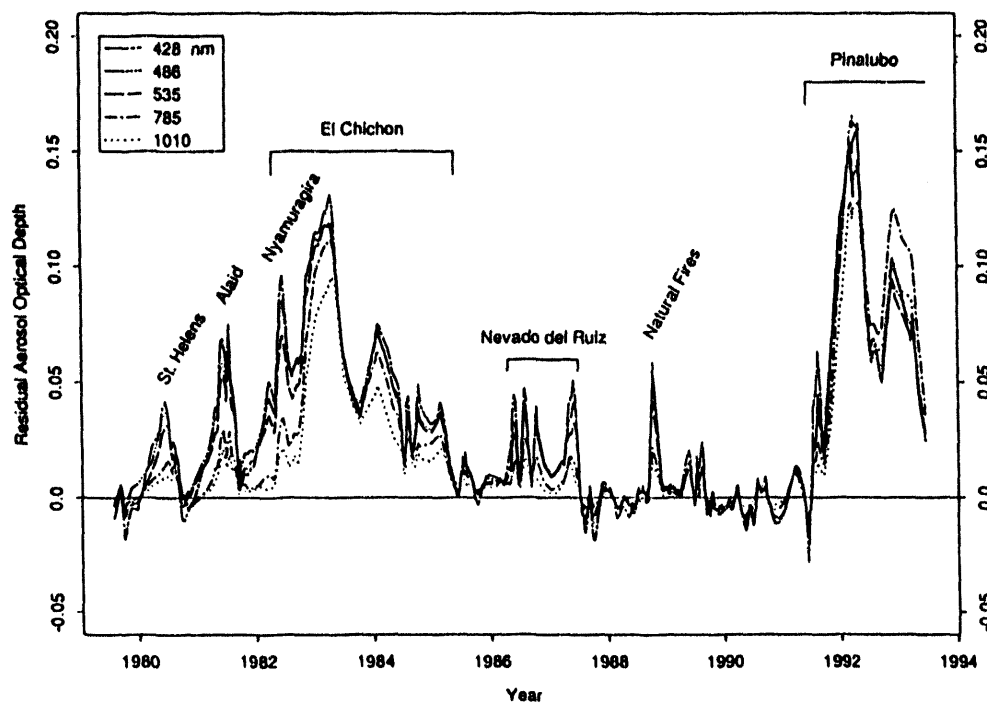
In the previous annual report (Laulainen et al. 1993), time-series data were presented that showed the effect of volcanic eruptions on aerosol optical depth at a midlatitude site. The time series of residual aerosol optical depth was extended with another year of data, as shown in Figure 3. The effects of the two major volcanic events (El Chichon and Mt. Pinatubo) are clearly seen. To highlight the Mt. Pinatubo eruption, the data are replotted on an expanded scale, as shown in Figure 4. The optical depth data were derived from direct solar beam measurements using an earlier radiometer, the Mobile Automated Scanning Photometer as described by Michalsky et al. (1990), at the Rattlesnake Mountain Observatory, Richland, Washington.

There are several interesting features to notice in Figures 3 and 4. First, the success in removing the seasonal background is indicated by the deviations around the zero residual optical depth line after the El Chichon and Nevado del Ruiz eruptions, but prior to Mt. Pinatubo. Second, the peak-smoothed extinction from Mt. Pinatubo is approximately 30% greater than that of El Chichon and is consistent with values reported by Dutton and Christy (1992). Third, similar to the behavior of El Chichon, a secondary maximum is observed to occur at the latitude of the Rattlesnake Mountain Observatory approximately 1 year after the primary Mt. Pinatubo peak. Fourth, the wavelength dependence of the residual extinction, especially the anomalously large values of extinction at 785 nm, appears to be quantitatively different for Mt. Pinatubo, particularly for the secondary maximum than for the other volcanic events, indicating differences in the evolution of the stratospheric aerosol size spectra. This behavior is most easily seen in Figure 4. Further analysis of this behavior is under way, and a paper is being prepared for publication in the open literature.





**FIGURE 3.** The Effect of Volcanic Perturbations on Aerosol Optical Depth at Five Wavelengths as Determined from Mobile Automated Scanning Photometer Observations and Rattlesnake Mountain Observatory Since 1979



**FIGURE 4.** Time-Series Behavior of the Mt. Pinatubo Stratospheric Aerosol Optical Depth at the Rattlesnake Mountain Observatory Showing Changes in Aerosol Particle-Size Evolution

Because of its establishment 6 months after the Mt. Pinatubo eruption, but just prior to the maximum stratospheric aerosol optical depth at northern midlatitudes, the Quantitative Links Network will be able to provide valuable information on spatial and temporal evolution of the stratospheric aerosol. This will, however, require that the network continue to operate for several years so that the background tropospheric aerosol burden and its seasonal variations can be established.

In addition to the above analysis, two papers were prepared for publication (Harrison and Michalsky 1993; Harrison et al. 1993) and three papers were presented at conferences this past fiscal year. One of these papers was on the effects and time-dependent behavior of Mt. Pinatubo aerosol and was presented at the Optical Society of America's topical meeting on Optical Remote Sensing of the Atmosphere in Salt Lake City, Utah, in March 1993 (Michalsky and Larson 1993). This paper describes the Mt. Pinatubo aerosol optical thickness as a function of time as measured at three sites: southeastern Washington; Boulder, Colorado; and Albany, New York. Two other papers were presented on the reduction in energy output of the Solar Electric Generating System concentrating power plant in southern California resulting from Mt. Pinatubo aerosol: one at the American Solar Energy Society's annual meeting in Washington, D.C., in April 1993 (Michalsky et al. 1993a) and one at a meeting of the International Solar Energy Society's meeting in Budapest, Hungary, in August 1993. A complete technical version of these two papers has been accepted for publication in *Solar Energy* (Michalsky et al. 1993b).

### Future Work

The major effort in FY 1994 will focus on the continued development and application of data analysis software. Analysis of data with respect to the Mt. Pinatubo eruption will continue.

Other significant activities include the following:

- upgrading the remaining six Quantitative Links Network units to the 32-channel logger during planned calibration visits
- calibration of all radiation sensor units in the spring and summer of 1994, including the precision infrared radiometers, assuming that the recalibration problems experienced with the precision infrared radiometers in previous years are resolved
- reduction of clear-day data using the automated data reduction technique developed at ASRC
- development or acquisition of additional algorithms to extract aerosol-size distributions, water vapor, and ozone total column from the aerosol optical depth data
- reformatting of X-modem binary files retrieved from the MFRSR into midnight-to-midnight multiday files to reduce the size of the archive and conversion of binary files to ASCII format, with the direct irradiance corrected for receiver cosine-response, and engineering units
- 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
- investigation of optical depths for opaque cloud cover; detection of opaque clouds by nulling the direct beam component; accumulating statistics on their frequency and thicknesses as measured by the diffuse irradiance component

- search for correlations between the measured parameters and the downwelling short-wave and long-wave irradiances, and, as they become available, between surface radiative fluxes and satellite-derived top-of-atmosphere long- and short-wave fluxes
- application of various numerical analysis packages to seek trends, categories, or variability patterns in the measured and derived parameters of radiation, such as cumulative frequency distribution
- submission of a paper on the effects of the Mt. Pinatubo eruption to *Geophysical Research Letters*.
- presentation of a paper on optical depth measurements with the MFRSR over the Quantitative Links Network at the American Meteorological Society Meeting in January 1994
- preparation of a paper on aerosol optical depth measurement and diffuse to direct irradiance ratios for submission to *Atmospheric Environment* or *Journal of Applied Meteorology*.

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Michalsky, J. J., R. Perez, R. Seals, and P. Ineichen. 1993b. "Degradation of Solar Concentration Performance in the Aftermath of Mt. Pinatubo." *Solar Energy* (in press).

## **Second-Generation Model**

**Principal Investigator: J. A. Edmonds**

The objective of the Second-Generation Model (SGM) project is to develop the scientific basis to make and bound projections of future energy-related emissions to the atmosphere of carbon dioxide and other radiatively important gases.

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### **FY 1993 Accomplishments**

During FY 1993, work focused on the continued development of the SGM, improvements on SGM Version 0.0 (including software enhancements), further development of the U.S. data base, and creation of international modules.

#### **Improved Data Sets**

The U.S. data base was further developed in an iterative process that resulted in the improved quality of the baseline scenario. Automating the development of input data sets continued. The input data sets for prices and technology were made more compact and easier to modify using an object-oriented conceptual framework. Using the new compact model input file structure, model inputs were extended through the year 2100. Work on debugging these input files was initiated. Development of a new method to enter new technologies into the model was completed. Biomass- and coal-based gas and liquid sub-sectors were added to the model input data set.

#### **Enhanced Software**

Several new options for recycling carbon tax proceeds were developed and implemented. Modifications to the computer code were made to facilitate running large batches of cases and analyzing the results. Issues with respect to the underlying theoretical behavior in the model were solved and implemented as part of the baseline process. Modifications were made to the overall process of executing the model, so that it is now possible to execute a series of runs

by simply running a .BAT file. Microsoft® Excel macros were developed that speed the printing of major results and present essential information in a graphic format. In preparation for the major model revisions to be undertaken over the next several months, an analysis of model memory requirements was made and strategies to reduce these requirements were developed.

#### **Added Sectors and Functions**

A series of tax cases was developed. A new facilities tax and an investment tax credit were added to the tax capabilities of the model. Work has begun on implementing detailed demand for energy services. Work on the design for Version 0.5 of the model continues, with considerable progress made on the household part of the design. Modifications to the emissions module were made to produce estimates of conventional air pollutant emissions. Further modifications included adapting the model so the latest U.S. Census midrange population forecast and Council of Economic Advisors' gross national product trajectory could be replicated by the model. The model inputs have been expanded to include sinks, global warming potential taxes, and additional technologies. Consideration of how to integrate water and land into the model continued.

#### **Initiated/Completed International Modules**

During FY 1993, five international modules were initiated or completed: Western Europe,

India, Japan, China, and Korea. Each of the modules is discussed separately.

- **Western Europe**--Mr. Richard Baron of Centre International de Recherche sur l'Environnement et le Développement in France ended his visit to PNL's Washington, D.C., office in November 1992. During FY 1993, he continued work on developing a Western Europe module under subcontract to PNL. This module should be up and running by the end of his projected visit in January 1994.
- **India**--Work on the India data set began in November 1992 with the arrival of Professor Pryadarshi Rampasad Shukla from the Indian Institute of Management in Ahmadabad, India. The reference case module was up and running in the summer of 1993, and the data have been developed and improved since that time. The SGM needed to be modified to allow for the significant differences between the Indian and U.S. economies. Work has begun on a case study of regional air quality regulation effects of greenhouse gas emissions. Professor Shukla is under subcontract to continue his support of these efforts.
- **Japan**--A collaborative agreement was established with Japan's National Institute for Environmental Studies (a government agency) in December, and Mr. Akira Hibiki visited from the institute in May 1993. Mr. Hibiki will be visiting PNL's Washington, D.C.,

office for 4 to 6 months, beginning in November 1993 to complete the module.

- **China**--Mr. Zhao Song from the China Energy Efficiency Center in the Peoples Republic of China arrived in February 1993. With his help, work began on the data set for China; this data set has almost been completed.
- **Korea**--Dr. Tae Yong Jung of the Korean Energy Economics Institute visited PNL's Washington, D.C., offices in June 1993 and began work on the Korean data set. During the second visit in November 1993, the Korean module became operational.

Negotiations were begun with the Prague Center for Energy Efficiency on developing a module for Eastern Europe.

In addition, Dr. Ronald D. Sands spent 6 weeks in the Netherlands visiting the Dutch National Institute for Public Health and Environmental Protection, working on agricultural and economic modeling issues in IMAGE II, the new Dutch global change model.

### **FY 1994 Objectives**

In FY 1994, the program will focus on the implementation of SGM Version 0.5; the continued development of international modules, including the completion of modules for Korea, Japan, Canada, Mexico, and Western Europe; and the establishment of an international SGM center in Seoul, Korea.

## **Carbon Dioxide Ocean Research**

**Principal Investigators:** J. P. Downing, W. E. Asher, D. W. Denbo, and E. D. Skyllingstad

The goals of the Carbon Dioxide (CO<sub>2</sub>) Ocean Research project are to develop improved models of ocean processes for climate research and new methods for estimating the carbon fluxes in the surface layer of the ocean. The objectives for FY 1993 were to 1) complete air-sea gas-exchange experiments in an outdoor wave tank; 2) make large eddy simulations of oceanic convection and surface layer mixing, using the Ocean Large Eddy Simulation Model (OLEM) developed in prior years; and 3) develop new technologies for measuring CO<sub>2</sub> in seawater. Major progress was made toward all of these objectives. First, construction and testing of an OLEM were completed and full-scale geophysical experiments were undertaken. During this past fiscal year, OLEM was used to understand the effects of wind, Stokes drift, and organized motions on mixing of the surface layer. OLEM was also used to determine that the Coriolis force and thermobaric effects are both essential mechanisms in modeling deep convection. Second, the first highly successful gas-exchange experiment in a large outdoor wave basin was completed. Third, work was completed on a new seawater sample container for CO<sub>2</sub> analysis and four automated CO<sub>2</sub> analyzers were delivered for the DOE-funded global CO<sub>2</sub> survey.

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### **FY 1993 Accomplishments**

The following sections give the details of the progress made on the above objectives in FY 1993.

#### **Air-Sea Exchange of CO<sub>2</sub>**

Field experiments were completed at Wild Rivers Waterpark, Irvine, California, to measure gas-exchange velocities for sulfur hexafluoride and helium, bubble void fraction, microwave emissivity, and foam coverage under realistic breaking waves. The analysis of data from the Georges Bank dual-tracer experiment, conducted in April 1990, was completed. Together, the Georges Bank and Wild Rivers data provide excellent support for our model relating gas-exchange velocities and whitecap area in the open ocean. The results revealed that the 1) linear dependence of gas-exchange velocity on whitecap area determined in the laboratory appears to hold for the open ocean, 2) total gas tension effects on bubble size distribution appear

to be significant, and 3) surface films appear to have a larger effect on gas invasion than on evasion. In the process of mobilizing for a second wave basin experiment in early FY 1994, the development of two new instruments was completed: a void fraction meter that measures the fractional volume of gas bubbles in near-surface waters and a system for recording the size distribution of near-surface bubble populations.

#### **Convection, Surface Processes, and Convection Parameterizations**

The three-dimensional version of OLEM is completely functional, and full-scale geophysical experimentation on oceanic convection and surface layer mixing processes is under way. Improvements made to OLEM during FY 1993 include the addition of drogues for flow visualization and investigations of advection effects on local diffusion and heat transfer. The drogues provide the capability to study the

response of natural and man-made particles to hydrodynamic forces in greater detail. Comparisons of convection simulations by OLEM with observations of convection in the atmospheric boundary layer showed that, with full rotation, OLEM mimics the atmospheric data very well. This is very encouraging because these data provide the only known test involving a real geophysical flow, unbounded by physical model walls, or a limited numerical domain. Recently completed experiments suggest that parameterizations of convection in climate models may have to include full rotation and thermobaric effects to correctly simulate the timing and magnitude of episodic convection in a coupled general circulation model.

OLEM also successfully simulated Langmuir circulations and demonstrated the importance of the Stokes drift parameterization and the resulting organized vertical motions on the behavior of the mixed layer. It is particularly noteworthy that when the Stokes drift is included in the model physics, it overwhelms other effects in driving subgrid-scale mixing and substantially increases the depth to which turbulent momentum exchange penetrates in the mixed layer. The work on OLEM has made it very clear that new field data will be needed in FY 1994 if detailed and credible validations of the model results can be made. Therefore, plans for FY 1994 include a controlled field experiment to provide these data.

### **CO<sub>2</sub> Survey Support and Technology Developments**

Ms. Linda S. Bingler spent more than 45 days at sea with scientists from the University of Hawaii and University of Miami, aboard the

R/V Thompson, during a World Ocean Circulation Experiment (WOCE) cruise to the Bering Sea and the North Pacific Ocean. While on this cruise, 2200 seawater samples were collected and analyzed for CO<sub>2</sub>. The results of the seawater analyses provide the first CO<sub>2</sub> data ever obtained in the Bering Sea and an excellent opportunity to compare CO<sub>2</sub> profiles from the North Pacific Ocean over a 20-year period.

Construction of the facility for evaluating the stability of pressure, conductivity, and other sensors at deep-ocean pressures was completed. Work was also completed on a new seawater sample container for the CO<sub>2</sub> Science Team. This container is made from a plastic/metal/plastic trilaminate material and has an innovative fitting that allows samples to be collected and dispensed without wasting seawater for rinsing. Short-term storage of seawater for CO<sub>2</sub> analysis was successfully demonstrated by the Scripps Institution of Oceanography.

### **Plans for FY 1994**

In the coming fiscal year, plans are to complete a second gas-exchange experiment in the wave basin at Wild Rivers Waterpark. This experiment will include the first set of concurrent measurements of gas-exchange velocities, whitecap area, turbulence, and microwave emissivity ever made under controlled conditions. Process studies with OLEM will be completed, focusing on the effects of Langmuir circulation on surface layer mixing and upper ocean structure in the equatorial Pacific Ocean. Additional experiments will be completed to delineate the climatic factors that influence deep convection and deep water formation.



# **Improved Parameterization for Deep Convection Processes in Ocean General Circulation Models**

**Principal Investigators:** T. Paluszkievicz and R. D. Romea

**Other Investigators:** E. D. Skyllingstad, D. W. Denbo, L. F. Hibler, and K. Strauss

A one-dimensional penetrative plume model was constructed to parameterize the process of deep convection in ocean general circulation models (OGCMs). In conjunction with the development of the parameterization, the Modular Ocean Model (MOM) (Pacanowski et al. 1991) and the Parallel Ocean Climate Model (POCM) (Semtner and Chervin 1988) were configured for the Nordic Seas and the process of preconditioning was simulated to develop a suitable test bed for the parameterization.

The research in FY 1994 will complete the incorporation of the parameterization in the OGCM. Sensitivity tests will be performed to determine whether the present method of using a restoring boundary condition on temperature and salinity will suffice for climate studies or whether full thermodynamic fluxes will be required to trigger deep convection. The parameterization will be tested for event scales of order years. We will also test the parameterization on longer time scales by collaborating with the Computer Hardware, Advanced Mathematics, and Model Physics Program (CHAMMP) investigators at the Los Alamos National Laboratory doing decadal length simulations. The ultimate goal of FY 1994 is to incorporate the improved physics into an OGCM that could be used in global climate research and, consequently, improve the deep water production process important to the carbon cycle and climate modeling.

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## **FY 1993 Accomplishments**

The goals and objectives accomplished over this past fiscal year were the following:

- completion of the one-dimensional vertical mixing model to parameterize deep convection
- testing and comparison of the one-dimensional model's performance against other models and against observations
- investigation of the sensitivity of preconditioning to different forcing, in comparison with theoretical models
- preparation of the parameterization and the OGCM for inclusion of the parameterization.

## **One-Dimensional Parameterization**

The development and testing of a one-dimensional penetrative plume model (OPPS; Ocean Parameterized Plume Scheme) that has the capability to parameterize the process of deep open-ocean convection in a vertical grid column of an OGCM was completed. The purpose of this parameterization was to improve OGCM simulations by including the physics of deep penetrative convection (thermobaric convection) and deep water formation, without adding the complexity of a full, large eddy simulation (LES). Accordingly, requirements for the model were the following: the essential physics must be parameterized in an OGCM grid volume, the code must be compact and fast, and the model should interface seamlessly with the OGCM

from time step to time step. As a consequence of this last requirement, the OGCM and the one-dimensional model interact column by column only through the state variables  $T(z)$  and  $S(z)$  in a grid column (where  $T$  is potential temperature,  $S$  is salinity, and  $z$  is a vertical coordinate). The one-dimensional model rearranges the thermodynamic variables vertically, consistent with vertical stability requirements and has no "memory" of previous time steps.

To accomplish this, the parameterization scheme takes the temperature and salinity profiles of OGCM grid boxes and simulates the subgrid-scale effects of convection using a one-dimensional parcel model. The one-dimensional model moves water parcels from the surface layer down to their level of neutral buoyancy, simulating the effect of convective plumes. While in transit, the plumes exchange water with the surrounding environment; however, the bulk of the plume water mass is deposited at the level of neutral buoyancy. Weak upwelling around the plumes is included to maintain an overall mass balance. The process continues until the negative buoyant energy of the one-dimensional vertical column is minimized. The parameterized plume entrainment rate, which plays a central role in the model physics, is calculated using modified equations based on Turner's (1973) entrainment hypothesis. This scheme differs from the convective adjustment techniques currently used in OGCMs because the parcels penetrate downward with the appropriate degree of mixing with the environment until they reach their level of neutral stability.

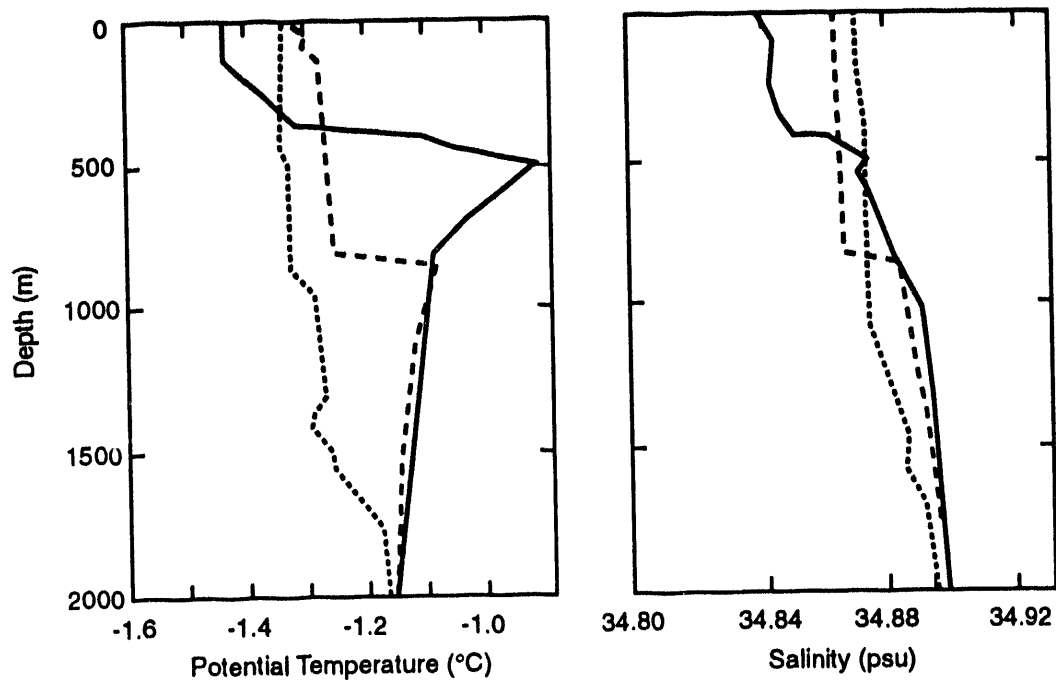
The one-dimensional model was tested against observations by initializing the model with hydrographic data and testing the ability to reproduce the time series of hydrography (Figure 1). The data are from the Greenland Sea Project (GSP) station D-6. The one-dimensional model is initialized with the GSP data from February and then correctly simulates the evolution of the deep mixing. In addition, the one-dimensional model was tested further by

comparison with the LES model results of Denbo and Skillingstad (1992). The LES model was initialized with hydrographic sections from the Greenland Sea, as was OPPS, and the time evolution was compared. The comparison with this model gave insight into the ability to simulate strongly thermobaric events; the depth of penetration, the evolution of the properties, and the time scale of the onset all compared favorably. Finally, the parameterization was tested against existing vertical mixing parameterizations, such as the Kraus-Turner-Killworth (KTK) buoyancy-forced mixed-layer model. The OPPS model compared well with the KTK model under general conditions and was able to perform under strongly thermobaric conditions, whereas KTK is unable to correctly simulate thermobaric penetrative convection.

## Oceanic General Circulation Model Simulations

The MOMs and POCMs were prepared for the simulation of preconditioning in the Nordic Seas. Using POCM, we simulated the preconditioned gyre by using a combination of heat flux and wind forcing. The wind forcing had the strength and characteristics of the strong, low-pressure systems that have been found in the Greenland Sea (Legutke 1991). The preconditioning of the Gulf of Lyon region in the Mediterranean Sea was also studied. These simulations revealed that the scale of the preconditioned gyre and the preconditioning response time varied, as expected, with the Rossby radius. As a consequence, the simulation of preconditioning is sensitive to the resolution used in the model.

The behavior of the gyre-scale circulation and its response to various wind and heat flux conditions is in agreement with the theoretical model of Romea (1976). Topography, cooling, and cyclonic circulation are the essential ingredients for preconditioning. Neither cooling nor a cyclonic circulation alone will bring about the elevation of the pycnocline that is necessary



a) Observations; Valdivia Cruise; — Stat 009 2/8/89, - - Stat 124 3/1/89, ... Stat 143 3/9/89

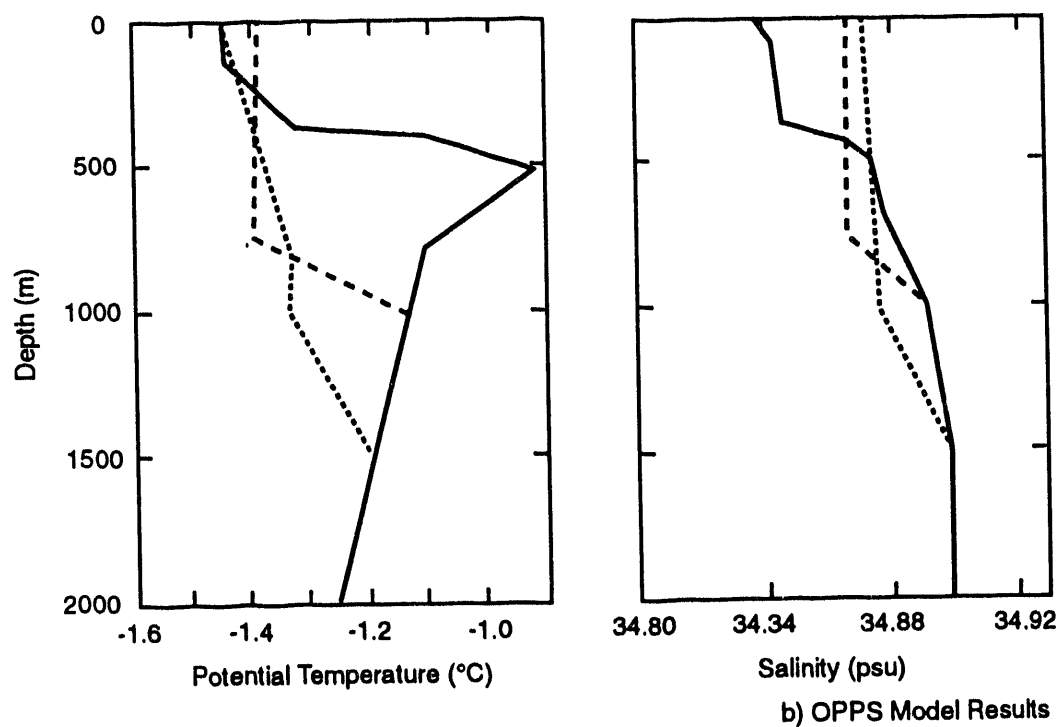


FIGURE 1. Consecutive Profiles of Temperature and Salinity from the Greenland Sea Project Station D-6, Showing the Rapid Deepening of the Convective Layer

to weaken the vertical stability and facilitate deep convective events.

### Goals for FY 1994

In the coming year, the insertion of the one-dimensional parameterization into MOM and POCM will be completed. The OGCMs, with the new parameterization, will be run for the Nordic Sea test basin and compared with a "twin" OGCM experiment that uses the standard convective adjustment algorithm. The results will be evaluated, as much as possible, against available data sets. As a part of this testing, the role of the surface boundary conditions in triggering deep convection events will be evaluated. In climate-scale simulations, a restoring surface boundary condition is used on the temperature and salinity fields. It is common to use a month time scale on the restoring time; the climatological monthly means are generally used as the forcing data sets. How well this method triggers deep convective events in comparison to using a heat flux and salinity flux boundary condition will be evaluated. Killworth (1983) and Chu and Gascard (1991) note that deep convection is believed to be triggered by a combination of preconditioning of the gyre-scale circulation along with intense cooling events. A better temporal resolution (than monthly mean) of these triggering mechanisms may be necessary to achieve the full value of the convective parameterization. The use of a heat and salt flux condition, as opposed to a monthly restoring boundary condition, could facilitate this temporal resolution and, ultimately, could facilitate coupling with the atmospheric models. To complete the development, how best to combine the convective parameterization with a wind-mixed layer parameterization will be determined. Also, how the parameterization may need to be modified once an ice model is coupled to the OGCMs

in use by other CHAMMP investigators will be further investigated.

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**Publications  
and  
Presentations**

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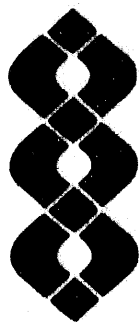
# Author Index

## Author Index

Abbey, O. B., 6  
Allwine, K. J., 11, 43  
Alzheimer, J. M., 51  
Anderson, G. A., 51  
Asher, W. E., 63  
Berkowitz, C. M., 1  
Berndt, J. L., 53  
Bian, X., 21, 43  
Busness, K. M., 1, 6  
Chapman, E. G., 1  
Chuang, C. C., 47  
Cress, T. S., 25  
Denbo, D. W., 63, 65  
Doran, J. C., 8, 15, 43  
Downing, J. P., 63

Easter, R. C., 47  
Edmonds, J. A., 61  
Furger, M., 21, 43  
Garrity, W. A., 6  
Ghan, S. J., 47  
Hannigan, R. V., 6  
Harrison, L. C., 53  
Hauser, R. K., 21  
Hibler, L. F., 65  
Hubbe, J. M., 11  
Larson, N. R., 53  
Laulainen, N. S., 53  
Leung, L. R., 47  
McCaa, J., 47

Michalsky, J. J., 53  
Paluszkiewicz, T., 65  
Penner, J. E., 47  
Romea, R. D., 65  
Saylor, R. D., 1  
Shaw, W. J., 1, 18, 51  
Skylvingstad, E. D., 63, 65  
Strauss, K., 65  
Stokes, G. M., 25  
Thorp, J. M., 1  
Warren, M. J., 6  
Whiteman, C. D., 21, 43, 51  
Wilczak, J., 43  
Zhong, S., 21



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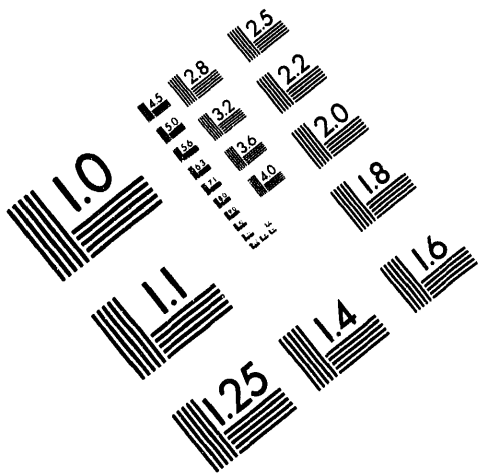
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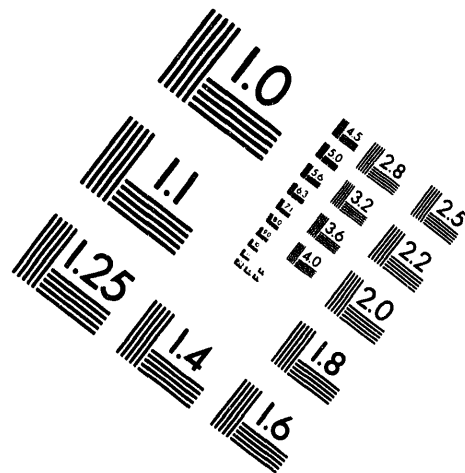
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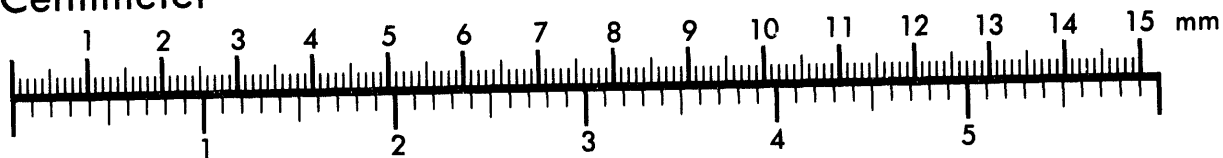
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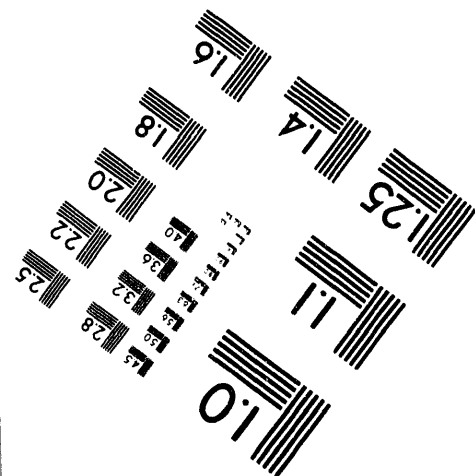
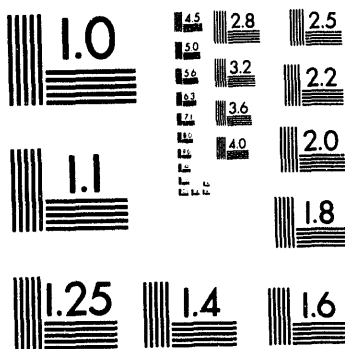
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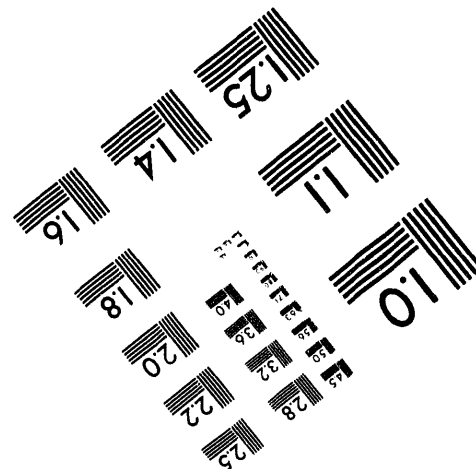
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C. M. Berkowitz K6-08  
X. Bian K6-11  
C. J. Brandt K6-98  
N. M. Burleigh K1-29  
K. M. Busness K6-08  
E. G. Chapman K6-08  
T. D. Chikalla P7-75  
J. F. Clarke BWO  
T. T. Claudson K1-66

E. A. Crecelius Sequim  
T. S. Cress K1-74  
M. T. Dana K6-08  
D. W. Denbo Sequim  
J. L. Devary K6-77  
J. C. Doran K6-11  
J. P. Downing Sequim  
S. L. Downs K2-05  
J. G. Droppo, Jr. K6-55  
R. C. Easter K6-08  
J. A. Edmonds BWO  
C. E. Elderkin K6-11  
S. J. Ghan K6-08  
C. S. Glantz K6-55  
W. A. Glass K3-53  
J. A. Glissmeyer K6-55  
D. W. Glover K6-96  
M. J. Graham K6-78  
R. H. Gray K1-33  
R. K. Hadlock K6-55  
R. V. Hannigan K6-08  
M. S. Hanson K1-51  
D. J. Hoitink K6-55  
L. A. Holmes K1-29  
J. M. Hubbe K6-11  
J. R. Johnson K3-57  
R. A. Keefe K6-11  
M. L. Knotek K1-48  
W. W. Laity K2-50  
N. S. Laulainen K6-08  
L. Y. Leung K6-08  
R. N. Lee P7-07  
A. M. Liebetrau K7-34

J. C. Liljegren K6-11  
C. C. Lumetta P7-58  
J. A. Mahaffey P7-82  
T. Paluskiewicz Sequim  
J. F. Park P7-52  
W. T. Pennell K1-74  
J. V. Ramsdell, Jr. K6-55  
R. D. Saylor K6-08  
M. J. Scott K8-15  
W. J. Shaw K6-11  
R. Shikar Seattle  
B. D. Shipp K8-28  
E. D. Skillingstad Sequim  
W.G.N. Slinn K6-08  
G. M. Stokes K1-74 (5)  
J. A. Stottlemire K6-75  
T. S. Tenforde K1-50 (2)  
J. M. Thorp K6-08  
R. A. Walters K1-50  
L. L. Wendell K6-11  
R. B. Westerberg K4-16  
C. D. Whiteman K6-11  
R. E. Wildung P7-54  
Health Physics Library  
Life Sciences Library (2)  
Public Reading Room  
Publishing Coordination  
Technical Report Files (5)

Routing

P. C. Hays K6-86  
B. V. Johnston (Last)

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