PNL-7600 Pt. 3
UC-402

Pacific Northwest Laboratory Annual Report for 1990 to the DOE Office of Energy Research

Part 3: Atmospheric and Climate Research

April 1991

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

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

Battelle

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

PNL-7600, Pt. 3
UC-402

Pacific Northwest Laboratory Annual Report for 1990 to the DOE Office of Energy Research

Part 3 Atmospheric and Climate Research

Staff Members of Pacific Northwest
Laboratory

April 1991

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

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This 1990 Annual Report from Pacific Northwest Laboratory (PNL) to the U.S. Department of Energy (DOE) describes research in environment, safety, and health conducted during fiscal year 1990. The report again consists of five parts, each in a separate volume.

The five parts of the report are oriented to particular segments of the PNL program. Parts 1 to 4 report on research performed for the DOE Office of Health and Environmental Research in the Office of Energy Research. Part 5 reports progress on all research performed for the Assistant Secretary for Environment, Safety and Health. In some instances, the volumes report on research funded by other DOE components or by other governmental entities under interagency agreements. Each part consists of project reports authored by scientists from several PNL research departments, reflecting the multidisciplinary nature of the research effort.

The parts of the 1990 Annual Report are:

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

Part 2: Environmental Sciences
Program Manager: R. E. Wildung — M. G. Hefty, Report Coordinator; D. A. Perez, Editor; K. K. Chase, Text Processor

Part 3: Atmospheric and Climate Research
Program Manager: C. E. Elderkin — W. R. Barchet, Report Coordinator; E. L. Owczarski, Editor

Part 4: Physical Sciences
Program Manager: L. H. Toburen — L. H. Toburen, Report Coordinator; K. A. Parnell, Editor

Part 5: Environment, Safety, Health, and Quality Assurance
Program Managers: L. G. Faust, R. V. Moraski, J. M. Selby — D. K. Hilliard, Report Coordinator and Editor

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

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

T. S. Tenforde
Health and Environmental
Research Program Office

Previous reports in this series:

Annual Report for

1951	HW-25021, HW-25709
1952	HW-27814, HW-28636
1953	HW-30437, HW-30464
1954	HW-30306, HW-33128, HW-35905, HW-35917
1955	HW-39558, HW-41315, HW-41500
1956	HW-47500
1957	HW-53500
1958	HW-59500
1959	HW-63824, HW-65500
1960	HW-69500, HW-70050
1961	HW-72500, HW-73337
1962	HW-76000, HW-77609
1963	HW-80500, HW-81746
1964	BNWL-122
1965	BNWL-280, BNWL-235, Vol. 1-4; BNWL-361
1966	BNWL-480, Vol. 1; BNWL-481, Vol. 2, Pt. 1-4
1967	BNWL-714, Vol. 1; BNWL-715, Vol. 2, Pt. 1-4
1968	BNWL-1050, Vol. 1, Pt. 1-2; BNWL-1051, Vol. 2, Pt. 1-3
1969	BNWL-1306, Vol. 1, Pt. 1-2; BNWL-1307, Vol. 2, Pt. 1-3
1970	BNWL-1550, Vol. 1, Pt. 1-2; BNWL-1551, Vol. 2, Pt. 1-2
1971	BNWL-1650, Vol. 1, Pt. 1-2; BNWL-1651, Vol. 2, Pt. 1-2
1972	BNWL-1750, Vol. 1, Pt. 1-2; BNWL-1751, Vol. 2, Pt. 1-2
1973	BNWL-1850, Pt. 1-4
1974	BNWL-1950, Pt. 1-4
1975	BNWL-2000, Pt. 1-4
1976	BNWL-2100, Pt. 1-5
1977	PNL-2500, Pt. 1-5
1978	PNL-2850, Pt. 1-5
1979	PNL-3300, Pt. 1-5
1980	PNL-3700, Pt. 1-5
1981	PNL-4100, Pt. 1-5
1982	PNL-4600, Pt. 1-5
1983	PNL-5000, Pt. 1-5
1984	PNL-5500, Pt. 1-5
1985	PNL-5750, Pt. 1-5
1986	PNL-6100, Pt. 1-5
1987	PNL-6500, Pt. 1-5
1988	PNL-6800, Pt. 1-5
1989	PNL-7200, Pt. 1-5

FOREWORD

At the start of FY 1990, the atmospheric sciences and carbon dioxide research programs within the Office of Health and Environmental Research (OHER) were gathered into the new Atmospheric and Climate Research Division (ACRD). One of the central missions of this new division is to provide the Department of Energy with scientifically defensible information on the local, regional, and global distributions of energy-related pollutants and their effects on climate. This information is vital to the definition and implementation of a sound national energy strategy. Because much of the work done at PNL during FY 1990 falls under the umbrella of the new ACRD, we are including in this volume the progress and status reports for all OHER atmospheric and climate research projects at PNL.

PNL has had a long history of technical leadership in the atmospheric sciences research programs within OHER. Within the ACRD the Atmospheric Chemistry Program (ACP) continues DOE's long-term commitment to study the continental and oceanic fates of energy-related air pollutants. This program is built on the research foundations established by the Multistate Air Pollution Power Production Study (MAP3S) and the Processing of Emissions by Clouds and Precipitation (PRECP) programs in the decades of the 70s and 80s. Research through direct measurement, numerical modeling, and laboratory studies in the ACP emphasizes the long-range transport and transformation of oxidant species, nitrogen-reservoir species, and aerosols. The Atmospheric Studies in Complex Terrain (ASCOT) program continues to bring basic research on density-driven circulations and turbulent mixing and dispersion in the atmospheric boundary layer to bear on the micro- to mesoscale meteorological processes that affect air-surface exchange and on emergency preparedness at DOE and other facilities.

The atmospheric sciences research within ACRD provides the basic scientific underpinnings to the emerging ACRD program on global climate research. Research projects with the core CO_2 and ocean research programs are now integrated with those in the Atmospheric Radiation Measurements (ARM), the Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP), and quantitative links programs to form DOE's contribution to the U.S. Global Change Research Program. The latter three programs, all initiated in FY 1990, have grown to be a major component of ACRD. Climate research in the ACRD 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 along two broad research areas:

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

This report describes the progress in FY 1990 in each of these areas. A divider page summarizes the goals of each area and lists projects that support research activities.

CONTENTS

PREFACE iii

FOREWORD v

ATMOSPHERIC RESEARCH 1

Atmospheric Diffusion in Complex Terrain, *J. C. Doran, K. J. Allwine, and J. M. Hubbe* 3
Heat Budgets of Valley and Basin Atmospheres During the Evening Transition and Nighttime Periods, *C. D. Whiteman* 5
Atmospheric Boundary Layer Studies, *D. C. Bader* 8
Atmospheric Chemistry Program/PRECP, *C. M. Berkowitz, K. M. Busness, M. Terry Dana, W. E. Davis, R. C. Easter, R. V. Hannigan, R. N. Lee, D. J. Luecken, D. S. Sharp, J. M. Thorp, and S. D. Tomich* 9
Continuing Development of the G-1 Aircraft, *K. M. Busness* 16

CLIMATE RESEARCH 21

The Atmospheric Radiation Measurement (ARM) Program: A Study of Radiation Forcing and Feedbacks, *G. M. Stokes* 23
Carbon Dioxide Ocean Research, *J. P. Downing, W. E. Asher, D. W. Denbo, E. D. Skyllingstad, and M. C. Richmond* 28
Progress Report on the Second Generation Model FY 1990, *J. A. Edmonds* 34
The Resources Analysis Research Project: A Methodology for Assessing Regional Economic Impacts of and Responses to Climate Change--the MINK Study, *M. J. Scott* 35

PUBLICATIONS 41

PRESENTATIONS 43

AUTHOR INDEX 45

DISTRIBUTION Distr.1

Atmospheric
Research

ATMOSPHERIC RESEARCH

Atmospheric research at PNL focuses primarily on two areas: the flow of air in complex terrain and the fate of emissions as they are transported and processed in the atmosphere. Analyses of airflow in complex terrain investigate the role of energy exchange, terrain configuration, and scale interactions for coupled flows (e.g., slope, valley, and gradient) in developing and destroying boundary-layer circulations and in dispersing contaminants. Analyses of the regional-scale transport of emissions have addressed the physical and chemical processes within cloud and precipitation systems, the inflow and outflow dynamic characteristics of clouds, microphysics and in-cloud scavenging properties, aqueous phase chemistry, regional wet deposition patterns, and storm chemistry climatology.

Research activities include field experiments, data analysis, and modeling simulations. Experiments provide data for analysis in both airflow and emission processing research, and modeling simulations provide a tool for predicting airflow and emission transport and mitigating their effects. This year, two field experiments were performed, analysis of data from previous experiments continued, and model development was advanced in both the examination of airflow in complex terrain and in the transport and processing of pollutants.

The two field programs supported by the projects whose progress is summarized in this report were a boundary-layer study in the Tennessee Valley and a precipitation chemistry study in Ohio. The Tennessee field program took place in February and March; its purpose was to gain a better understanding of the local thermally developed circulations that form in the Tennessee Valley and their interaction with the synoptic scale flows above the valley and to support improvements in emergency forecasting operations at Oak Ridge National Laboratory (ORNL). The Frontal Boundary Study, conducted in October 1989 in the vicinity of Columbus, Ohio, addressed the vertical redistribution of pollutants by cyclonic storm systems.

Numerical computer models are used to help analyze the results of measurement programs and to carry out numerical experiments that extend the range of conditions being studied. Models under development at PNL include those that simulate mesoscale air flow in complex terrain and those that simulate the transport and removal of pollutants through deposition or reaction on regional and global scales. These investigations are systematically increasing the reliability of theoretical descriptions and models. Such models hold the promise of translating descriptive and forecasting capabilities to the great number of other locations where boundary-layer flow and contaminant dispersion and removal are significantly influenced by terrain features, surface energy exchange processes, regional characteristics of meteorology and atmospheric chemistry.

Presentation of research results is an important mechanism for cooperative improvements in atmospheric studies. In addition to the presentation of conference papers and publication of journal articles, a peer review by the National Academy of Sciences examined the work at PNL under the pollutant transport project. Details of the favorable response by the review committee are forthcoming.

The following articles present summaries of the progress in FY 1990 under these research tasks:

- **Atmospheric Boundary-Layer Studies**
- **Atmospheric Diffusion in Complex Terrain**
- **Coupling/Decoupling of Synoptic and Valley Circulations**
- **Nonlinearity/Acid Precipitation Processing**
- **Research Aircraft Operations.**

Atmospheric Research

Atmospheric Diffusion in Complex Terrain

J. C. Doran, K. J. Allwine, and J. M. Hubbe

The Atmospheric Diffusion in Complex Terrain program carried out several modeling, measurement, and analysis tasks during the past year. These tasks focused on the collection, interpretation, and understanding of a large quantity of meteorological and tracer data collected in Brush Creek valley in Colorado, at Oak Ridge in Tennessee, and on the Hanford Site in Washington.

Modeling Studies

A series of numerical experiments was carried out to study the effects of ambient winds on the development and structure of katabatic winds forming in a valley. The work was prompted by an analysis of the data obtained from the 1984 ASCOT experiment in Brush Creek valley in Colorado. Clements et al. (1989) reported that the depth of the down-valley drainage flows in Brush Creek showed an inverse linear dependence on the magnitude of the wind speed in the first 100 m above the valley ridgetops. Because of the limited duration of the field experiments, Clements et al. were able to consider only four cases, two of which were quite similar in wind speed. The use of a numerical model to extend the range of ambient winds that could be studied appeared useful; it also provided the opportunity to examine possible mechanisms that might be responsible for the observed behavior.

Clark's nonhydrostatic, anelastic code (Clark 1977; Clark and Farley 1984) was chosen for the simulations. The valley geometry used for the numerical experiments was based roughly on that of Brush Creek, although some simplifications were made for convenience. Ambient ridgetop winds ranged in speed from 0.5 to 6 m/s, and made angles with the valley axis ranging from 0° (up-valley) to 90°. Cooling of the valley was based on measured values of sensible heat fluxes taken from the 1984 field measurements. Model runs were typically carried out for 6 h of cooling after an initial 2-h spinup period. A nested, inner model was spawned and used for the last 2 h of cooling to provide better spatial resolution in the valley.

For some parts of the valley, the observed linear decrease of drainage depth with wind speeds in a 100-m-thick layer above the ridgetops was found, but near the valley mouth this relationship broke down. Figure 1 shows profiles of wind speeds in the center of the valley at a point 6.5 km from the valley mouth. The dependence of drainage depth on wind speed is apparent. The dependence of the depth and strength of the katabatic winds on ambient wind direction was less clear. As the approach angle α increases, the strength of the updrafts and downdrafts near the windward wall of the valley and near the valley mouth increases. Figure 2 shows an example of this behavior, for α = 10° and 60°, at a height 100 m below the ridgetop. Such vertical motions enhance mixing processes and can entrain the ambient up-valley winds into

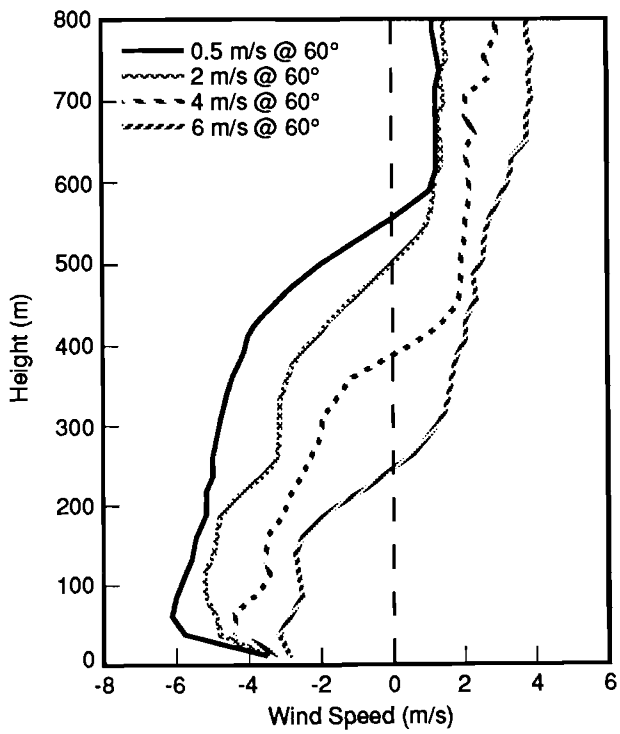

FIGURE 1. Along-Valley Wind Speed Profiles at Center of Valley for y = 24 km, α = 60°, and Ambient Wind Speeds of 0.5, 2, 4, and 6 m/s. Positive values are upvalley speeds and negative values are down-valley speeds.

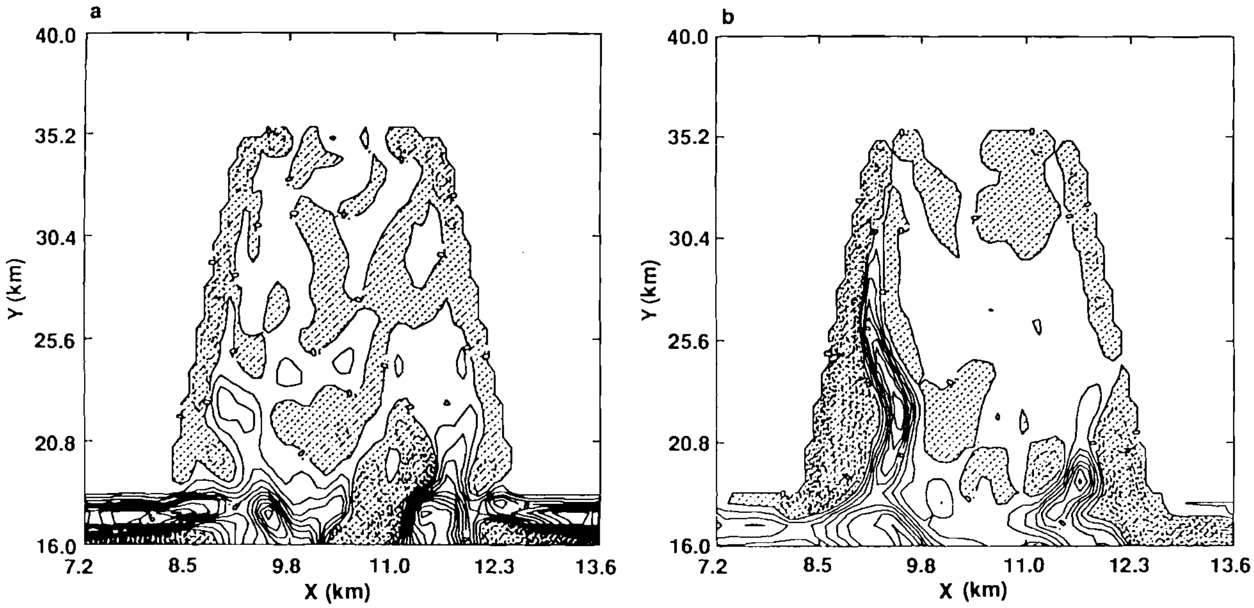

FIGURE 2. Vertical Velocities at a Height of 600 m for (a) $\alpha = 10°$ and (b) $\alpha = 60°$, for Ambient Wind Speed of 4 m/s. Stippled areas are negative velocities; contour interval = 0.2 m/s.

the valley. However, as α increases, the component of the ambient wind directed up-valley also decreases so that the entrained air carries less up-valley momentum. The two factors apparently compensate to a large extent, leaving the depth of the down-valley wind regime relatively unchanged.

In a second study, a numerical mesoscale model has been used to study wind patterns over the Hanford Site. This work was carried out in cooperation with the Meteorological Services and Assessment Program. A case was selected for investigation in which the winds in the southern part of the site were blowing strongly from the southwest while the area around the Hanford Meteorological Station (HMS) was nearly calm. These conditions are not uncommon during winter months, but their occurrence and timing can be difficult to predict reliably. Sensitivity tests were conducted to examine the range of geostrophic forcing, vertical shears, and initial inversion structures that would result in the observed wind and temperature patterns. Preliminary results suggest that only a relatively narrow range of ambient wind directions (e.g., at 1000 m AGL) from the northwest will be effective in producing the specified conditions. The role of blocking by Rattlesnake Ridge and the effects of cold stagnant air in the northern regions of the Site are currently being studied further.

Field Experiment

A field measurement program was conducted in the Tennessee Valley near Oak Ridge during late February and early March. This effort was jointly supported by the three ASCOT programs at PNL; plans for the program were reported last year by Doran and Whiteman (1990). A tethered balloon was used to gather wind and temperature profile data, which will be combined with data obtained from other ASCOT investigators to obtain a picture of the wind and temperature fields in the Oak Ridge area and its surroundings. The dependence of these fields on the ambient conditions above the surrounding ridgetops will be the subject for continuing investigations during the coming year. Initial analyses have identified several nights in which marked directional shear was observed in the vertical wind profiles. The role of terrain channeling and thermal forcing in explaining these features will be investigated.

Data Analysis

Finally, the Eulerian integral conservation equation for a scalar quantity was applied to the analysis of the 1984 ASCOT tracer data collected in Brush Creek valley, Colorado. It was found that even for near-steady nighttime flows, with no sources or sinks in a control volume and no mass flow through the side, top, or bottom boundaries, a mass balance could not be obtained by considering only the advection terms. A slight oscillation (10%) in the along-valley winds and a lack of measurements of tracer throughout the control volume produced an uncertainty in the budget that could not be resolved.

The magnitude of this uncertainty was investigated using the one-dimensional conservation equation with no sources, sinks, or molecular diffusion. Inflow boundary conditions for the scalar of varying amplitude and frequency were imposed and the velocity was also allowed to vary as a periodic function in time. It was found that the storage term in the equation can be roughly twice the amplitude of the product of the scalar and the velocity. Another source of uncertainty in the analysis is a longitudinal turbulent flux term that appears in the equation. Preliminary calculations put this term at a maximum of 5% to 10% of the total advection term.

This study shows that the use of the integral conservation principle in the analysis of most experimental data can provide, at best, only a rough (~30% to 200%) balance in the scalar quantity being investigated. However, this approach might still be useful in the estimation of certain quantities that would otherwise be difficult to estimate, such as a diffuse source term. With an experiment designed to reduce the uncertainties in each term of the conservation equation, the desired quantity could be estimated as a residual.

References

Clark, T. L. 1977. "A Small-Scale Dynamic Model Using a Terrain-Following Coordinate Transformation." *J. Comp. Phys.* 24:186-215.

Clark, T. L., and R. D. Farley. 1984. "Severe Downslope Windstorm Calculations in Two and Three Spatial Dimensions Using Anelastic Interactive Grid Nesting: A Possible Mechanism for Gustiness." *J. Atmos. Sci.* 41:329-350.

Clements, W. E., J. A. Archuleta, and D. E. Hoard. 1989. "Mean Structure of the Nocturnal Drainage Flow in a Deep Valley." *J. Appl. Meteor.* 28:457-462.

Doran, J. C., and C. D. Whiteman. 1990. "Planning for the Oak Ridge 1990 Experiment: Climatology and Modeling." In *Pacific Northwest Laboratory Annual Report for 1989 to the DOE Office of Energy Research*, PNL-7200 Pt. 3, Pacific Northwest Laboratory, Richland, Washington.

Heat Budgets of Valley and Basin Atmospheres During the Evening Transition and Nighttime Periods

C. D. Whiteman

In recent years there have been several attempts to calculate individual components of the heat budgets of various valleys and basins (Hennemuth 1985; Freytag 1985; Maki et al. 1986; Vergeiner et al. 1987; Horst et al.1987, 1989; Kondo et al. 1989) . The impetus for this work has generally been the desire to gain a better understanding of the role of the valley's heat budget in generating local thermally driven circulations.

As one activity under the Coupling/Decoupling of Synoptic and Valley Circulations Project, Whiteman (1990) presented a conceptual framework for such calculations, comparing individual terms in several valleys and basins where bulk budget terms were estimated, and drawing conclusions regarding the meteorology of valley and basin atmospheres during the evening transition and nighttime periods. This article summarizes this research. We proceed by stating the mathematical form of the atmospheric heat budget equation, developing a conceptual model for intercomparing various valleys and basins, and evaluating the heat budgets for three different valleys and basins.

Atmospheric Mass and Heat Budgets

From the First Law of Thermodynamics, the atmospheric heat budget equation for a volume v can be written as

$$\int \left[\underbrace{\rho c_p \frac{\partial \bar{\theta}}{\partial t}}_{a} = \underbrace{-\rho c_p \nabla \cdot \left(\bar{\mathbf{V}}\,\bar{\theta}\right)}_{b} \underbrace{-\rho c_p \nabla \cdot \left(\overline{\mathbf{V}'\theta'}\right)}_{c} \underbrace{-(\theta / T)\,\nabla \cdot \mathbf{R}}_{d} \right] dv \qquad [W] \qquad (1)$$

where c_p is specific heat at constant pressure, θ is potential temperature, T is temperature, **V** is the vector wind, and **R** is the vector net all-wave radiation.

Equation (1) specifies that the rate of change of heat storage in an atmospheric volume (term a) depends on the convergence of potential temperature flux by the mean wind (term b), convergence of turbulent sensible heat flux (term c), and convergence of radiative flux (term d) in the atmospheric volume. Clearly, the magnitudes of the individual terms in Equation (1) depend on the size of the valley or basin. In order to allow comparisons between valleys of different size, we normalize Equation (1) by dividing each of the terms by the valley drainage area A such that the units of the terms become W m^{-2}.

Conceptual Model

We consider the bulk heat budgets of valley and basin atmospheres under constraints of mass and heat conservation. In a draining valley, mass conservation requires that air flowing down the valley axis must be replaced by air that sinks into the valley from above. Because the valley atmosphere is stable during the evening transition and nighttime periods, this replacement air is warmer than the air in the valley and must be cooled in order for it to participate in the drainage flow. This sinking may occur preferentially in a layer above the sidewalls where proximity to the cooling surfaces is maximized, but sinking may also occur over the valley center or tributaries. Sensible heat flux convergence (term c) and radiative flux convergence (term d) are typically negative at night and thus tend to produce cooling in the valley atmosphere. Nighttime observations in valleys also generally show a net loss from valley heat storage (term a is negative). The remaining term in Equation (1) represents advection. Vertical sinking motions in a stable atmosphere produce warming, so that the vertical component of this term is expected to produce warming. Horizontal along-valley advection generally produces cooling, and horizontal cross-valley advection simply redistributes heat within the valley volume with no net effect on the bulk heat budget. The sum of the advective components (i.e., term b) is expected to produce a net warming that counters the cooling contributed by other terms of the heat budget. We can thus think of the air subsiding into the top of the valley atmosphere as the "brake" on the valley thermal wind system. The wind system attains a steady state when a balance is attained between the advective warming, caused predominantly by the warm air that sinks into the top of the valley and the cooling processes that occur within the valley. The strong rate of cooling that is a feature of the valley atmosphere early in the evening becomes much weaker once the along-valley drainage begins, since the heat budget terms that produce cooling become counteracted by the subsidence warming necessary to sustain the mass flow.

In a completely closed basin, the air within the basin in the late afternoon is simply cooled in place, and little interchange occurs with the air above the basin. The mass balance is therefore characterized by a stagnation, and subsidence warming does not play the important role in the basin atmosphere that it plays in a draining valley. Since all the remaining terms in the heat budget produce cooling, the basin atmosphere experiences a more or less continuous cooling throughout the night, undiminished by the onset of subsidence warming. One should keep in mind that completely closed basins are quite unusual topographically, and most basins will have a drainage channel and thus some subsidence heating. In closed basins such as sinkholes, meteor craters, etc., minimum temperatures can be quite extreme and the few studies of atmospheric cooling in such basins show a strong cooling, as expected (e.g., Sauberer and Dirmhirn 1954).

Calculation of heat budget terms is complicated by non-ideal topography and, in practice, it is sometimes difficult to choose the atmospheric volume in which to make meaningful calculations because of unequal ridgetop heights, rapidly dropping ridgelines, etc. Further, one might expect changes in the atmospheric heat budget along a valley's axis, since subsidence may be enhanced above the head of a valley and compensatory rising motions may occur near the foot of a valley. Most atmospheric heat budgets to date have been accomplished for the nighttime "steady-state" period, and no calculations have yet been performed for the morning and evening transition periods. During daytime, the mixed layer in the valley can grow beyond the ridgetops so that the concept of a fixed control volume within the valley becomes inappropriate.

Heat Budget Equation Terms for Three Valleys

Table 1 shows calculations of the individual terms in Equation (1) for three different valleys and basins. These terms have been normalized by dividing by the valley drainage areas, as explained above. In the case of Colorado's 650-m-deep Brush Creek valley (Horst et al. 1987, 1989), the calculations were made over a 3.4-km-long valley segment at the lower end of the valley. The segment had a drainage area of about 10 km^2. Calculations for Japan's 1090-m-deep Aizu Basin were obtained from a paper published by Kondo et al. (1989), which stated the drainage area as 5710 km^2. The Sinbad Basin calculations were made for a 550-m-deep, dry Canyonlands basin on the border of Colorado and Utah with a drainage area of 83.8 km^2.

For the Aizu Basin calculations by Kondo et al. (1989), the advection term (term b) was assumed negligible. Since the basin is not closed, however, we have illustrated the results with an alternative assumption (in parentheses in Table 1) that the advection term produces warming at the rate of 25 W m^{-2}, in conformance with the Sinbad Basin calculations.

Calculations show that radiative and sensible heat flux convergences (i.e., the diabatic terms) are negative and are thus responsible for the nighttime cooling of basins and valleys. Of these two terms, model calculations suggest that the radiative term is the weakest. Sensible heat flux convergences, calculated as a residual in the atmospheric heat budget, are quite large--in the neighborhood of -30 to -100 W m^{-2}. Advection results in net warming of the valley and basin atmospheres. This warming is stronger in valleys than in basins, although the fact that the Sinbad Basin has an appreciable drainage rate decreases the contrast between this basin and the Brush Creek valley. The net effect of the diabatic cooling and the advective warming is a nocturnal loss of heat storage. The rate of loss varies from valley to valley and there are significant uncertainties in calculations of individual terms. Trapped volumes (e.g., basins) cool more rapidly than well-drained volumes. Although not shown in Table 1, well-drained valleys have a strong initial rate of cooling that decreases substantially once the down-valley flow begins. Warmer air above the valley feeds the valley drainage flows and acts as a thermodynamic brake on the down-valley wind system because import of warm air at the valley's head counters the thermally developed pressure gradient that drives the down-valley flow.

Heat budget computations for the three valleys and basins reveal discrepancies between surface sensible heat flux observations and sensible heat flux divergences calculated as atmospheric heat budget residuals. It is suggested that these discrepancies arise because the sensible heat flux measurements made on the valley floors are not representative of the larger heat fluxes on the sidewalls and because significant upward turbulent sensible heat fluxes may occur at the tops of the valley control volumes. These upward sensible heat fluxes have been assumed to be small in all

TABLE 1. Nighttime Atmospheric Heat Budget Terms (W m^{-2} for Colorado's Brush Creek valley, Japan's Aizu Basin, and Colorado's Sinbad Basin).

	Location and Date			
Heat Budget Term	Brush Creek 9-26-84	Brush Creek 9-30-84	Aizu Basin Oct. Apr. May	Sinbad Basin 7-15-88
Change of Heat Storage	-10	-25	-46	-45
Convergence of Flux by Mean Wind	31	77	0 (25)	25
Radiative Flux Convergence	-7	-8	-9	-17
Sensible Heat Flux Convergence (Residual)	-34	-94	-37 (-62)	-53
Surface Sensible Heat Flux (Measured)	-18	-33	0	7
Imbalance	16	61	37 (62)	46

budget calculations to date. Model simulations of valley heat budgets are presently being performed as part of the ASCOT program to evaluate such assumptions (Bader and Horst 1990).

References

Bader, D.C., and T.W. Horst. 1990. "Model Evaluation of the Assumptions Used in Valley Energy Budgets." In *Preprints, Fifth Conference on Mountain Meteorology*. American Meteorological Society, Boston, Massachusetts.

Freytag, C. 1985. "MERKUR-Results: Aspects of the Temperature Field and the Energy Budget in a Large Alpine Valley During Mountain and Valley Wind." *Contrib. Atmos. Phys.* 58:458-476.

Hennemuth, B. 1985. "Temperature Field and Energy Budget of a Small Alpine Valley." *Contrib. Atmos. Phys.* 58:545-559.

Horst, T. W., K. J. Allwine, and C. D. Whiteman. 1987. "A Thermal Energy Budget for Nocturnal Drainage Flow in a Simple Valley." In *Preprints, Fourth Conference on Mountain Meteorology*, pp. 15-19, American Meteorological Society, Boston, Massachusetts.

Horst, T. W., D. C. Bader, and C. D. Whiteman. 1989. "Comparison of Observed and Simulated Nocturnal Valley Thermal Energy Budgets." In *Extended Abstracts, International Conference on Mountain Meteorology and ALPEX*, Deutsches Forschungsanstalt für Luft - und Raumfahrt, DLR, Oberpfaffenhofen, Germany.

Kondo, J., T. Kuwagata, and S. Haginoya. 1989. "Heat Budget Analysis of Nocturnal Cooling and Daytime Heating in a Basin." *J. Atmos. Sci.*, 19:2917-2933.

Maki, M., T. Harimaya, and K. Kikuchi. 1986. "Heat Budget Studies on Nocturnal Cooling in a Basin." *J. Meteor. Soc. Japan* 64:727-740.

Sauberer, F., and I. Dirmhirn. 1954. "Über die Entstehung der Extremen Temperaturminima in der Doline Gstettner-Alm [On the Occurrence of Extreme Temperature Minimums in the Gstettner-Alm Sinkhole]. *Arch. Meteor. Geophys. Bioklim., Ser. B* 5:307-326.

Vergeiner, I., E. Dreiseitl, and C. D. Whiteman. 1987. "Dynamics of Katabatic Winds in Colorado's Brush Creek Valley." *J. Atmos. Sci.* 44:148-157.

Whiteman, C. D. 1990. "Energetics of Valley and Basin Atmospheres During the Evening Transition and Nighttime Periods." *Preprints, Fifth Conference on Mountain Meteorology*, pp. 266-268, American Meteorological Society, Boston, Massachusetts.

Atmospheric Boundary Layer Studies

D. C. Bader

In recent years, the Atmospheric Boundary Layer Studies project has focused on the dynamics and turbulence of boundary layers over flat terrain, simple slopes, and mountain valleys. This research has relied on the use of state-of-the-art numerical models and recently developed remote-sensing instrumentation to build an integrated observational and numerical modeling project. Accomplishments in FY 1990 include:

- preparation of a journal article describing the factors that affect nocturnal boundary layer development over the Roan Plateau, the landform that surrounds the Brush Creek valley
- comparison of observed and modeled valley energy budgets
- preliminary development work for new miniature acoustic sounding systems
- continued exploration of full-turbulence simulation (FTS) and large-eddy simulation (LES) modeling methods as useful tools to describe atmospheric boundary layer turbulence.

More detail on each of these activities is described below.

The development of the nocturnal boundary layer above the sloping Roan Plateau, which is situated upwind of a high mountain barrier, was studied through a combination of observations and numerical model simulations. The results showed that when there is a component of wind into the barrier, a two-layer nocturnal boundary layer develops in which a strongly stable region near the surface is topped by a deeper, but less stable transition region. This transition layer buffers the thermally produced topographic winds from the overlying synoptic winds flowing in the opposite direction. The two-layer structure persists in both summer and winter, which may provide a partial explanation for the seasonal consistency of the thermal wind systems in the underlying valleys.

Lidar wind measurements made during the 1984 ASCOT field experiment in Brush Creek were combined with vertical temperature soundings to quantify the mass and energy budgets of the nocturnal valley wind system. A nonhydrostatic mesoscale model was then employed to simulate the wind system in a simplified version of the real valley to help explain the inconsistencies found in the calculated budget. Results from this comparison were presented by Bader and Horst (1990).

This project supported the design and acquisition of a mini-SODAR (SOund Detection And Ranging) as part of an effort to enhance our remote sensing capability. The mini-SODAR is designed to be suitable for long-term unattended operation with remote data communications capability. The instrument will be included in the array of wind sounding equipment that will be deployed in upcoming Front Range studies. In the future its high-resolution low-altitude wind data would complement a radar profiler for a more complete sounding station. An expert in boundary-layer remote sensing technology was hired this year, with support coming partially from this project.

The use of full turbulence simulation (FTS) and large-eddy simulation (LES) numerical models are being explored as tools to formulate improved descriptions of turbulent flows in neutral and stable layers over both flat terrain and simple slopes. Collaborative work with Dr. James J. Riley at the University of Washington, an expert in FTS methods, was started this year and will continue in FY 1991. A PNL staff member who is currently on educational leave is undertaking a doctoral program under Dr. Riley's guidance with funding provided by this project.

Reference

Bader, D. C., and T. W. Horst. 1990. "Model Evaluation of the Assumptions Used in Valley Energy Budgets." In *Preprints, Fifth Conference on Mountain Meteorology*, American Meteorological Society, Boston, Massachusetts.

Atmospheric Chemistry Program/ PRECP

C. M. Berkowitz, K. M. Busness, M. Terry Dana, W. E. Davis, R. C. Easter, R. V. Hannigan, R. N. Lee, D. J. Luecken, D. S. Sharp, J. M. Thorp, and S. D. Tomich

Fiscal year 1990 was a transition year for the PRECP program, a shifting from regional and national-scale research issues related to acidic deposition under the NAPAP-oriented PRECP, to global environment studies under the new Continental and Oceanic Fate of Energy Related Air Pollutants project, part of the Atmospheric Chemistry Program (ACP). The major tasks of FY 1990, reflecting this shift, were:

- the Frontal Boundary Study (FBS), a field program directed toward regional deposition model evaluation as well as the global implications of cyclonic storm pollutant transport and processing
- initial development of a global chemical model (GChM)
- continued development of diagnostic precipitation scavenging models (e.g., Pluvius and the RADM Scavenging Module [RSM]).

Frontal Boundary Study

The FBS was conducted early in FY 1990, in the vicinity of Columbus, Ohio. The overall rationale and objectives for FBS, a summary of facilities and strategies, and a preliminary summary of the storms sampled during the field effort were presented by Busness et al. (1990) in last year's annual report. In brief, FBS served two purposes: 1) as the seventh in a series of field projects--the first six under the NAPAP-related PRECP program--investigating pollution removal processes and wet deposition model evaluation; and 2) as an initial field effort addressing an objective of ACP, namely, to assess the vertical redistribution of pollutants by cyclonic storm systems.

The major components of the experimental design were the PNL Gulfstream-1 aircraft and a network of sequential precipitation collectors. The experimental plan--which included all types of weather conditions, but emphasized warm fronts--called for flight operations over the ground sampling network in nearly all situations. The network consisted of 36 sites within an 80 x 80 km area immediately northeast of Columbus (CMH). Each site was equipped with a computer-controlled automated rain sampler (CCARS) (Tomich and Dana 1990), which provided rainfall data (0.25 mm [0.01 in.] resolution) and up to 9 sequential samples for chemical analysis (nominally 2.5 mm [0.1 in.] resolution).

The timed precipitation data from the CCARS, along with chemical analyses of the sequential samples for major inorganic ionic species, form data bases that allow a variety of spatial and temporal analyses, such as evaluation of spatial variations over time periods as short as 15 minutes.

Of the four significant precipitation events during the operational period, the one most studied to date is that of October 17, 1990, which included a cold front and the remnant of the tropical depression Jerry. Figures 1 and 2 show the spatial pattern of rainfall rate and sulfate concentration in rain during a 1-h period. Considerable variability in chemistry and precipitation rate in space and time was observed for this event; in contrast, the two warm sector events and another cold front showed much more uniformity.

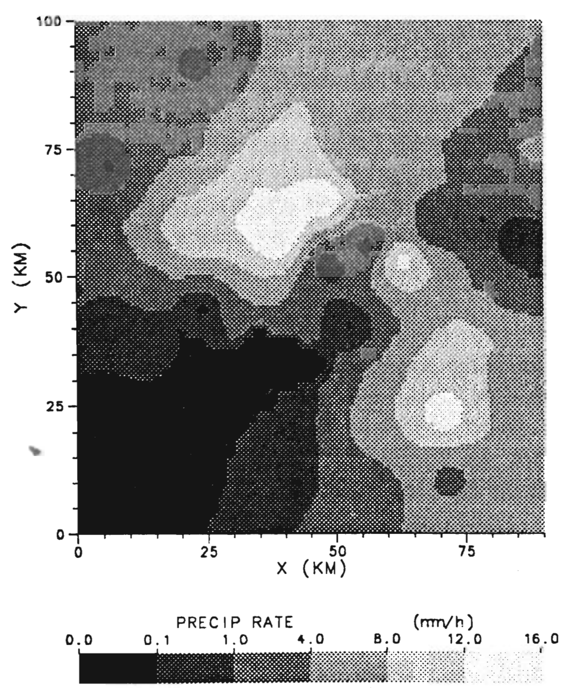

FIGURE 1. Spatial Pattern of Rainfall Rate at FBS Study Area on October 17, 1990.

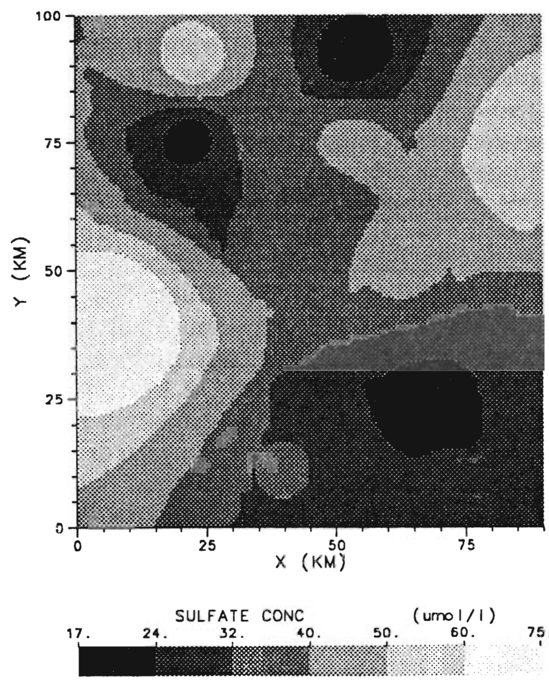

FIGURE 2. Spatial Pattern of Sulfate Concentration at FBS Study Area on October 17, 1990.

The data bases of air chemistry and spatially resolved precipitation chemistry from these events should prove invaluable in the evaluation of grid-scale performance of wet deposition models, and will provide excellent opportunities for analysis using higher dimensional models, such as Pluvius. Results concerning the primary FBS objective, relating to the redistribution and processing of pollutants by cyclonic storms, will follow more detailed analyses which are only in the preliminary stages.

Global Chemical Model (GChM)

The GChM has been developed at PNL to address the need for a justifiable and comprehensive description of both cloud and chemical processes occurring over large areas and long time periods. The GChM is a three-dimensional Eulerian model that can simulate tropospheric chemical and cloud processes occurring over various time and distance scales ranging from 1 day (regional) to over 1 year (hemispheric).

During 1990, several improvements were added to the model, and more detailed meteorological data sets were procured. Preliminary applications of the model were performed, where the effects of clouds and rain on the trans-Atlantic transport of sulfur species from North America and Europe were computed. Simulations were performed for two 30-day periods: climatologically typical January and July. Figure 3 shows concentrations of sulfate from anthropogenic plus natural sources, contoured on a logarithmic scale, in ppbv (gas-phase mixing ratio equivalent). There are maxima in sulfate concentrations over the areas of the largest sources in North America and Europe, and the influence of continental sources extends far over the ocean. Figure 4 shows the corresponding fractional contributions of sulfate from North American anthropogenic sources to the total sulfate air concentrations. North American sources appear in this simulation to contribute less than 5% of the total air concentrations of sulfate measured in Europe. A more detailed description of the GChM and recent results is being prepared for open literature submittal.

In the coming year, we plan to make several important improvements to the GChM. An advanced cloud parameterization scheme is being developed and implemented, and changes are being made to allow the model to use meteorological data from a variety of sources, including from a forecasting model. We are also planning to implement a more complete chemical mechanism, which will allow calculation of concentrations of nitrogen species and their photochemical products. Another improvement will allow an interactive feedback between chemical concentrations in the model and radiative processes in the Global Circulation Model. This capability will allow quantitative examination of the importance of the numerous positive and negative feedback loops in the global chemical/climate system.

Diagnostic Storm Modeling

Field data are important in validating the realism of diagnostic models; that is, to be useful a model must reproduce observed characteristics. Tests were run on two diagnostic models this year: Pluvius II, using data from the PRECP-II experiment conducted in 1985, and the RADM scavenging module (RSM), using data from the FBS.

Mesoscale Modeling of Precipitation Scavenging by a Cold-Frontal Squall Line

A cold-frontal squall line that occurred during the PRE-STORM/PRECP-II experiment (Daly et al. 1986) was simulated using Pluvius-II, a three-dimensional mesoscale reactive scavenging

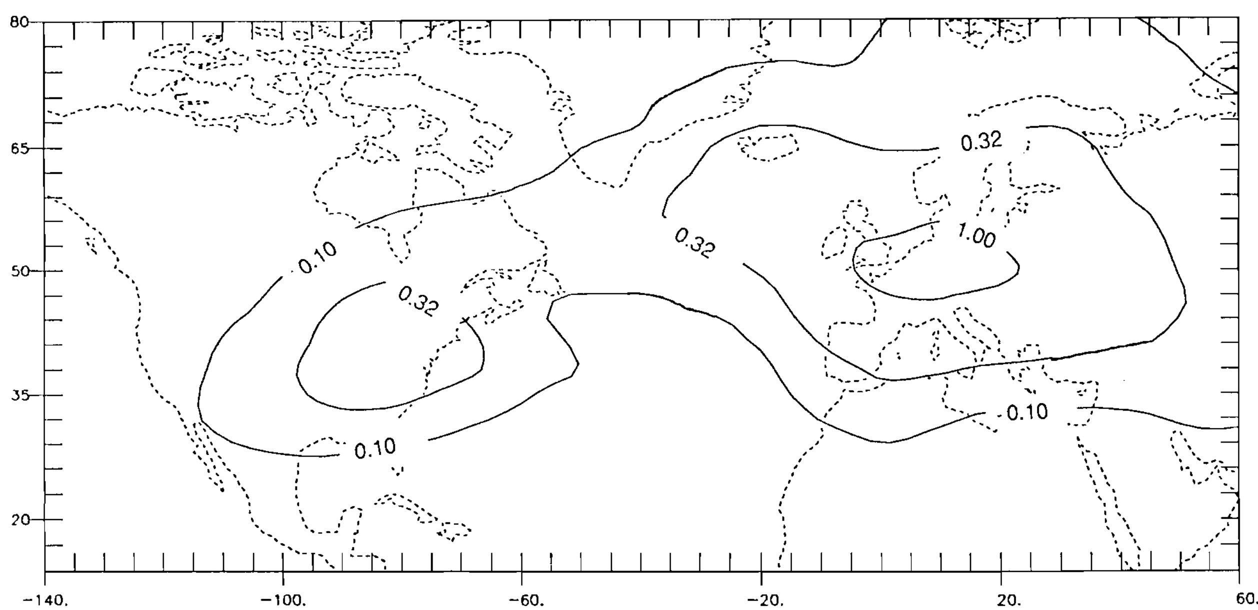

FIGURE 3. GChM Concentrations of Sulfate.

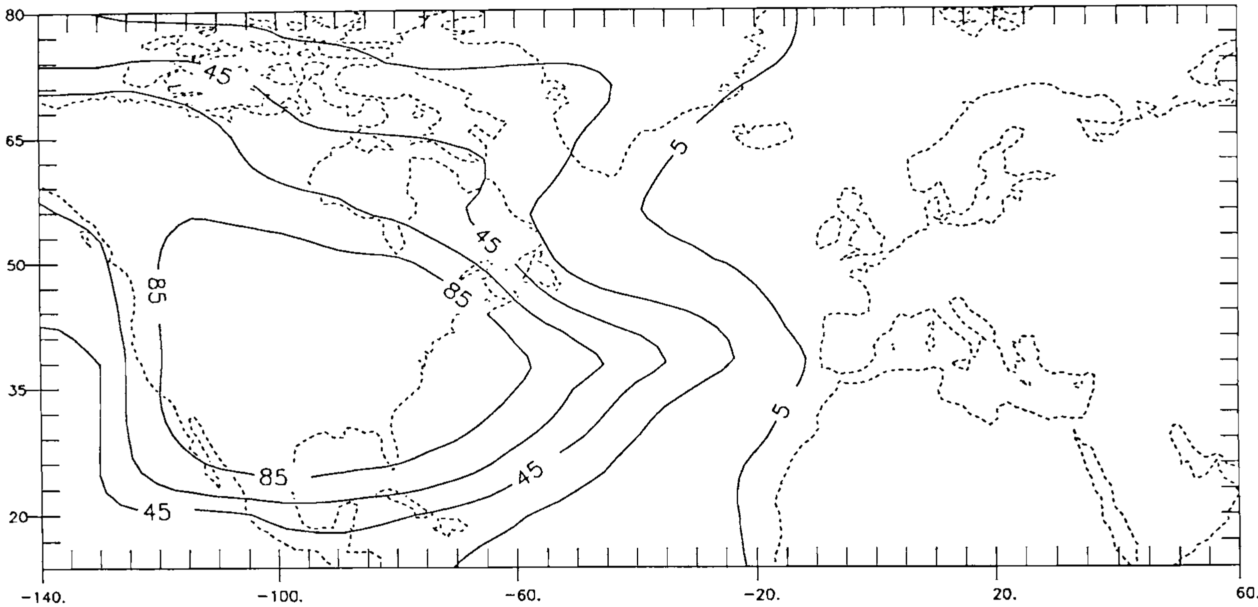

FIGURE 4. Fractional Contributions of Sulfate from North American Anthropogenic Sources to the Total Sulfate Air Concentrations.

model. The squall line was observed as it passed through Oklahoma on June 26, 1985. Measurements obtained during the experiment included a network of nine wet-only precipitation chemistry samplers and two air chemistry aircraft (PRECP-II component), and surface and airborne Doppler radar, an upper-air sounding network, and a surface meteorological network (PRE-STORM component).

The event was simulated using Pluvius-II (Hales 1989; Easter and Luecken 1988) coupled with the Colorado State University Regional Atmospheric Modeling System (RAMS). The RAMS model performed a 3-dimensional dynamical simulation of the squall line. The model was operated in a channel mode with a horizontal domain of 150 km in the across-front direction and 30 km in the along-front direction. Propagation speed of the line and cloud height were well reproduced; average precipitation amount was underpredicted by a factor of two. Precipitation scavenging was simulated by Pluvius-II, using air motion and cloud microphysics fields from the RAMS simulation. Pollutant concentrations in inflow air were specified using the air quality aircraft observations. Concentrations of sulfur, nitrate, and ammonium species were 0.5 to 1 ppb, and most sulfur was present as sulfate aerosol.

Figure 5a shows simulated and observed concentrations of sulfate in precipitation, and Figure 5b shows corresponding deposition amounts. Simulated sulfate concentrations agreed well with observations, both in terms of mean values and spatial variability. Deposition amounts of these species were underpredicted by a factor of two, similar to the precipitation underprediction. This is attributed to an underprediction of the inflow of water vapor and pollutants to the storm, as estimated from the upper-air soundings. Results for ammonium were similar to those for sulfate. Concentrations of nitrate in precipitation were underpredicted by a factor of two. Observed scavenging ratios for nitrate were a factor of two higher than those for sulfate and ammonium, suggesting possibly an unaccounted-for source of nitrate in precipitation or possible measurement difficulties with the low levels of nitrate and nitric acid that were present.

Use of the FBS Data to Evaluate the RADM Scavenging Model

The validity of the RSM (Berkowitz et al. 1989) was tested using the surface chemistry observed during the FBS. The FBS, as described earlier in this article, provided a series of data with

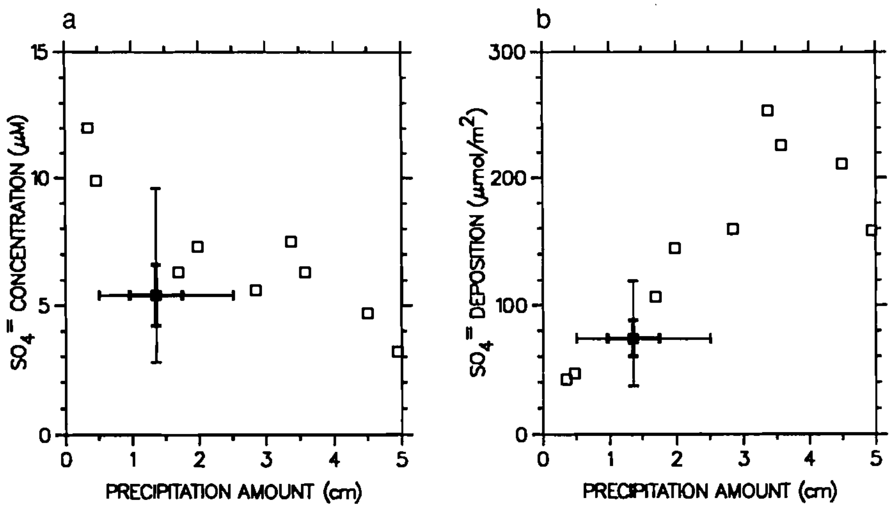

FIGURE 5. Observed and Simulated Concentrations of Sulfate in (a) Precipitation and (b) Deposition Amounts. Open squares are observations; solid squares are simulated results. The error bars on the simulated results show the range of values (outer error bars) and standard deviation of values (inner error bars) over the model spatial domain.

concurrent meteorological and chemical observations; both are necessary to evaluate a scavenging model.

The RSM was developed to provide a fast and comprehensive cloud/deposition model to operate within the regional-scale air pollution/ transport model (RADM) of Chang et al. (1987). The RSM was designed around several adjacent vertical columns, each connected to the other. Two columns are given to describing a convective storm (which characterizes the strong updrafts, relatively large liquid water concentrations and small fractional area of coverage) and a third column describes a stratiform storm (occupying a large area, and having very small liquid water concentrations). These two main components of the scavenging model provide a detailed vertical description of many key cloud features, including liquid water versus height and particle fall speed versus height. Together they define a cloud system having an area-average precipitation rate consistent with either modeled or observed values. A relatively simple, though nonlinear, chemical mechanism has been put into the RSM. SO_2 is oxidized by either H_2O_2 or O_3, and scavenging processes for gas, aerosols, and cloud microphysical processes are included. The microphysical scavenging rates are consistent with the rates defined by the cloud models.

Results of running the RSM have shown some sensitivities that affect model results. Studies by Scott and Luecken (1990) have shown that surface chemistry predictions from the RSM are quite sensitive to the fraction of rain produced by convective clouds (R) and to the fractional area of coverage by convective clouds (f_c). Figure 6, from this work, shows that a wide range of values is possible by adjusting these two parameters. It may be expected that other scavenging models would show a similar sensitivity.

Another area of uncertainty is related to the initial conditions for the simulations. Some vertical profiles of species were relatively easy to characterize, i.e., H_2O_2. Other species, such as SO_2, were not so cooperative. To evaluate how well the initial profiles must be known for scavenging calculations, we performed a series of simulations in which five base-case profiles of SO_2 were distorted in various ways, e.g., changing the scale height of the profiles, increasing or decreasing the mixing height, or simply truncating the profiles at the top of the boundary layer. Figure 7 shows the results of this study for the convective system. Each ellipse in this figure groups points that correspond to one of the 5 base-case profiles mentioned above (having a surface mixing ratio of 20, 10, 5, 2.5, and 1 ppb). Despite a wide number of permutations, it is seen that the exact shape does not

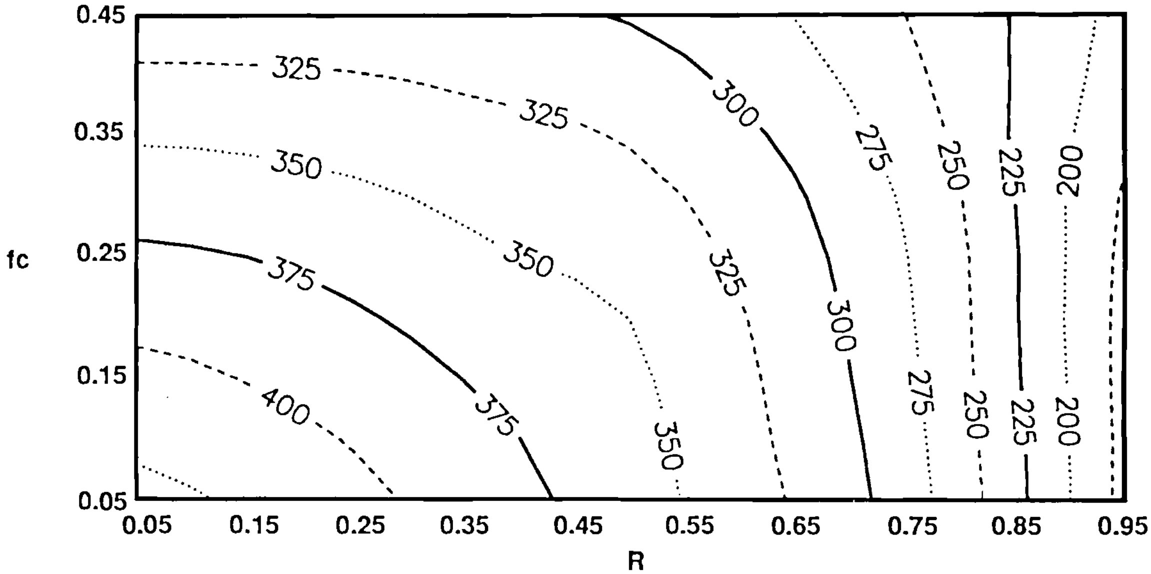

FIGURE 6. Sensitivity of the RSM to Meteorological Input. A range of deposition values is predicted as the fraction of total precipitation derived from convective clouds (R) and the fraction of total area covered by precipitating convective clouds (f_c) vary.

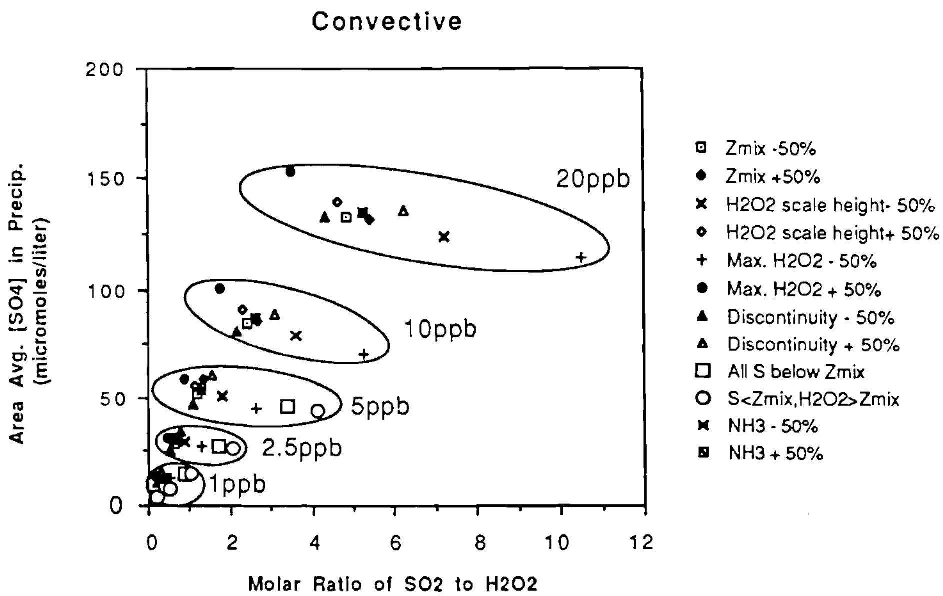

FIGURE 7. Results of Simulations Using Five Base Case Profiles of SO_2.

matter so much as getting the correct ratio of SO_2 and H_2O_2. Variations in the shape introduce an uncertainty of ~±6 µmol/L (giving a range of 12 µmol/L). A similar study for the stratiform storm resulted in a slightly higher element of uncertainty, of about ±10 µmol/L (giving a range of 20 µmol/L).

The FBS network data also provided an objective estimate of the area of convection based on an analysis of the individual precipitation records. Each record was assumed representative of a given area of the network, allowing evaluation of that part of the network receiving convective precipitation via

$$a_c = \frac{\sum_{n=1}^{36} A_n \Delta t_n \delta_n}{\sum_{n=1}^{36} A_n \Delta t_n}, \quad \delta_n = \begin{cases} 1, \text{ if } J_n > J^* \\ 0, \text{ if } J_n < J^* \end{cases}$$

where A_n and Δt_n refer to the area and time interval over which precipitation rate J_n occurred, and J^* is the minimum rate associated with convection.

Figure 8 shows the observed and predicted sulfate concentrations. The error bars for the observed values show one standard deviation of the values measured over the network during the hour indicated. The error bars for the predicted values reflect the uncertainty associated with defining the initial profiles and with defining the ratio of convective to total precipitation.

It is seen that the model-predicted values are within one standard deviation of the observations for the first 2 h of the simulation. Beginning with the third hour, the mean values of observed and predicted concentrations start to diverge; different assumptions about the meteorology would let the model produce better agreement. By 5 h, the model has removed enough mass so that the predicted values start to decrease, until by the end of the 7-h simulation, the predicted values are smaller than the observed. Whereas the FBS network was experiencing an inflow of fresh pollutant, this information was not available to the RSM, as it would be when the RSM is run within a regional-scale model that takes this important process into account.

Figures 9 and 10 show similar patterns for ammonium and nitrate. A sensitivity study for these species has not yet been performed on the gas-phase profiles; as a result, error bars cannot be put around the modeled points shown. It might be expected that the uncertainty would be comparable to those error bars shown in Figure 8.

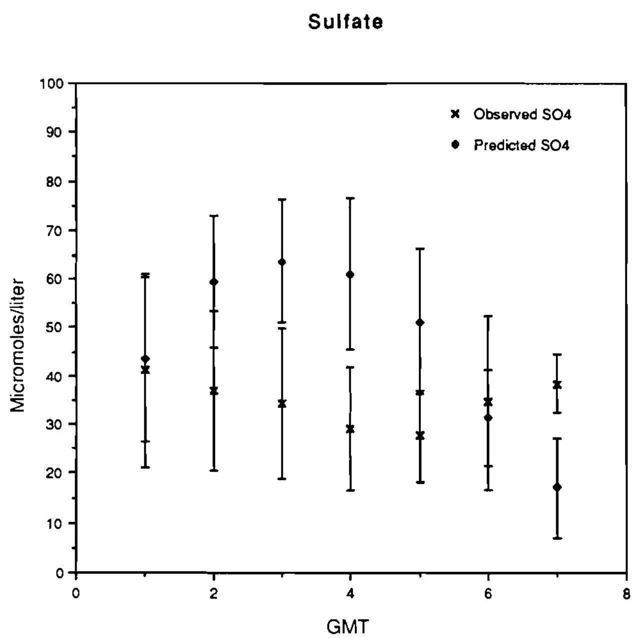

FIGURE 8. Observed and RSM-Predicted Sulfate Concentrations.

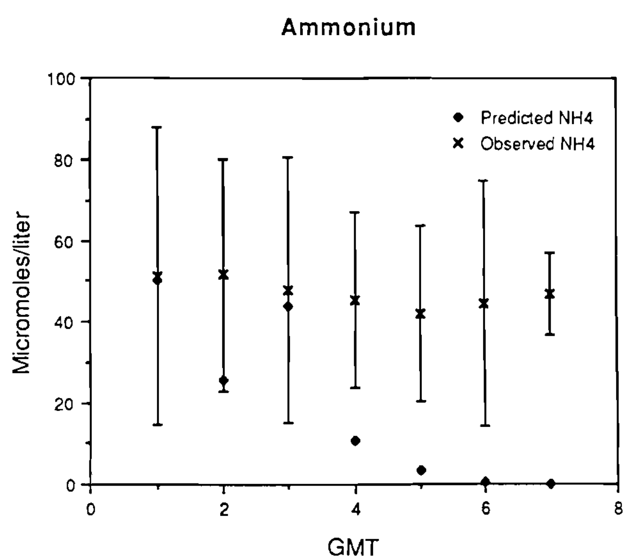

FIGURE 9. Observed and RSM-Predicted Ammonium Concentrations.

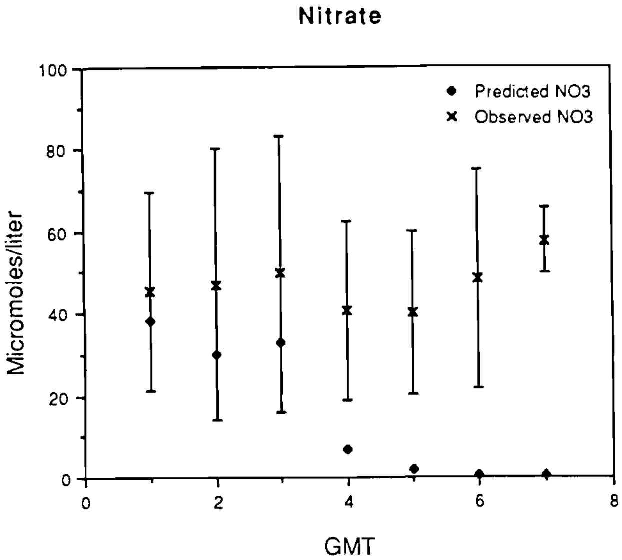

FIGURE 10. Observed and RSM-Predicted NO_3 Concentrations.

National Academy of Sciences Review

In September 1990, a review of the entire ACP was conducted by the National Academy of Science's Committee on Atmospheric Chemistry. Six presentations detailed PNL contributions to the ACP. The committee's report and recommendations are expected to be released in early 1991.

References

Berkowitz, C. M., R. C. Easter, and B. C. Scott. 1989. "Theory and Results from a Quasi-Steady-State Precipitation-Scavenging Model." *Atmos. Environ.* 23:1555-1571.

Busness, K. M., M. Terry Dana, W. E. Davis, D. W. Glover, R. V. Hannigan, R. N. Lee, D. J. Luecken, J. M. Thorp, and S. D. Tomich. 1990. "Overview of the Frontal Boundary Study." In *Pacific Northwest Laboratory Annual Report for 1989 to the DOE Office of Energy Research*. PNL–7200 Pt. 3, Pacific Northwest Laboratory, Richland, Washington.

Chang, J. S., R. A. Brost, I. S. Isaksen, S. Madronich, P. Middleton, W. R. Stockwell, and C. J. Walcek. 1987. "A Three-Dimensional Eulerian Acid Deposition Model: Physical Concepts and Formulations." *J. Geophys. Res.* 92:14,682-14,700.

Daly, D. S., M. T. Dana, A.C.D. Leslie, C. G. Lindsey, and W.G.N. Slinn. 1986. "PNL's Contributions to PRECP-II (PRE-STORM)." In *Pacific Northwest Laboratory Annual Report for 1985 to the DOE Office of Energy Research*. PNL-5750 Pt. 3, Pacific Northwest Laboratory, Richland, Washington.

Easter, R. C., and D. J. Luecken. 1988. "A Simulation of Sulfur Wet Deposition and Its Dependence on the Inflow of Sulfur Species to Storms." *Atmos. Environment* 22:2715-2739.

Hales, J. M. 1989. "A Generalized Multidimensional Model for Precipitation Scavenging and Atmospheric Chemistry." *Atmos. Environment* 23:2017-2031.

Scott, B. C., and D. J. Luecken. 1990. "The Response of Precipitation Chemistry to Storm Meteorology." Submitted to *Atmospheric Environment.*

Tomich, S. D., and M. Terry Dana. 1989. "Computer Controlled Automated Rain Sampler (CCARS) for Rainfall Measurement and Sequential Sampling." *J. Oceanic and Atmos. Technology* 7:541-549.

Continuing Development of the G-1 Aircraft

K. M. Busness

To support DOE and other programs in atmospheric research, PNL currently operates the Gulfstream 1 (G-1) twin-turboprop aircraft, shown in Figure 1. Initial development of the aircraft for research purposes was begun in 1988 (Busness and Hales 1988; Busness 1989), when several basic systems to provide power control and distribution, sample flow, and instrument mounting were designed, constructed, and implemented. Since that time, the aircraft has performed successfully in several air chemistry measurement studies, such as the Frontal Boundary Study conducted in the fall of 1989 (Busness et al. 1990), and in preliminary cloud characterization studies in support of the Atmospheric Radiation Measurement (ARM) program.

Since being put into service, the G-1 'platform' has undergone several modifications to enhance its

FIGURE 1. PNL Gulfstream 1 (G-1) Aircraft.

value as a research measurement vehicle. A high-performance data acquisition system, providing improved capability and reliability, was developed and installed in the aircraft, and has flawlessly performed in three intensive measurement campaigns. The system consists of an M200[a] processor (AT286) with color monitor and remote flat-panel display, floppy and hard disk drives, 1/4-in. magnetic tape drive, 32 channel 16-bit multiplexer/analog-to-digital conversion subsystem, 16-bit digital input/output subsystem, Loran interface, Particle Measuring Systems (PMS)[b] spectrometer probe interfaces, and serial communication interfaces. The system functions with a user-configurable, table-driven software package that enables the operator to easily modify most aspects of data acquisition, storage and display. Extensive real-time display options provide for text display of parameters, both as voltages and as computed engineering units, time-series displays of parameters in a continuing strip-chart format, parameters as a function of other parameters (e.g., altitude), PMS probe activity, and aircraft track and position plotted on preselected area maps.

Processing of the data collected on the aircraft is now accomplished on a newly-acquired Sun Sparcstation 1, with a 1/4-in. tape drive that is compatible with the aircraft system. This system is sufficiently compact to be transported to field sites, so that in-the-field, quick-look processing of the data can be done to ensure correct functioning of measurement and data acquisition processes and to extract information for timely planning of continuing aircraft missions. Final data processing can be accomplished either in the field or at home base, once appropriate instrument calibration factors have been determined, using a specialized PNL-developed software package, G1tool, to process the raw aircraft data files on the Sun system. G1tool makes extensive use of on-screen graphics as it allows the scientist to examine, flag, calibrate, edit, and plot the various recorded parameters. Its

(a) Science Engineering Associates, South Willington, Connecticut.
(b) Particle Measuring Systems, Boulder, Colorado.

functional routines are written as macros of commands from the statistics package called 'S,' and a user interface, employing screen windows and control panels, is written in the C language, all functioning under a UNIX operating system. An important feature of the G1tool software is its extensive use of automatically implemented operator activity logs, which document the data processing task and serve as a valuable element of the data quality assurance record.

In another major modification to the G-1, cloud-droplet and aerosol spectrometer probes were externally mounted on the aircraft nose section (see Figure 2). Reinforcing structure was added to the nose bulkhead aft of the radome, and deiced struts were attached to each side of the nose to provide mounting for the two probes. Each probe is about 100 cm long and 18 cm in diameter and weighs 18.2 kg. The sampling inlets extend 89 cm from the aircraft fuselage. The mounting attachments at the probes were designed to permit adjusting the angle of attack of the probes with the relative air stream. On the left side of the aircraft can be seen the forward scattering spectrometer probe (FSSP), an instrument used to count and characterize the size of cloud droplets in the range of about 3 to 47 μm by detecting particle light-scattering in an internally produced laser beam. An active scattering aerosol spectrometer probe, mounted on the right side of the nose, operates in a similar manner but characterizes the smaller airborne particles (ambient aerosol) in the 0.12 to 3 μm size range. The outputs from both probes are interfaced to the aircraft data acquisition system through specialized logic boards contained in the M200 chassis, so that these data can be acquired, recorded, and displayed simultaneously with other measurements.

To further enhance G-1 capabilities for performing cloud-chemistry/physics investigations, a scheme for deploying liquid cloud water collectors was developed and installed, and a specialized probe and sampling system for measuring particle aerosol within cloud droplets was installed and tested during the FBS field experiment. The two cloud water collectors are modified versions of those described by Huebert et al. (1988), based on the Mohnen slotted-rod design (Winters et al. 1979). Streamlined aluminum housings were attached to the escape hatch on the aircraft forward upper

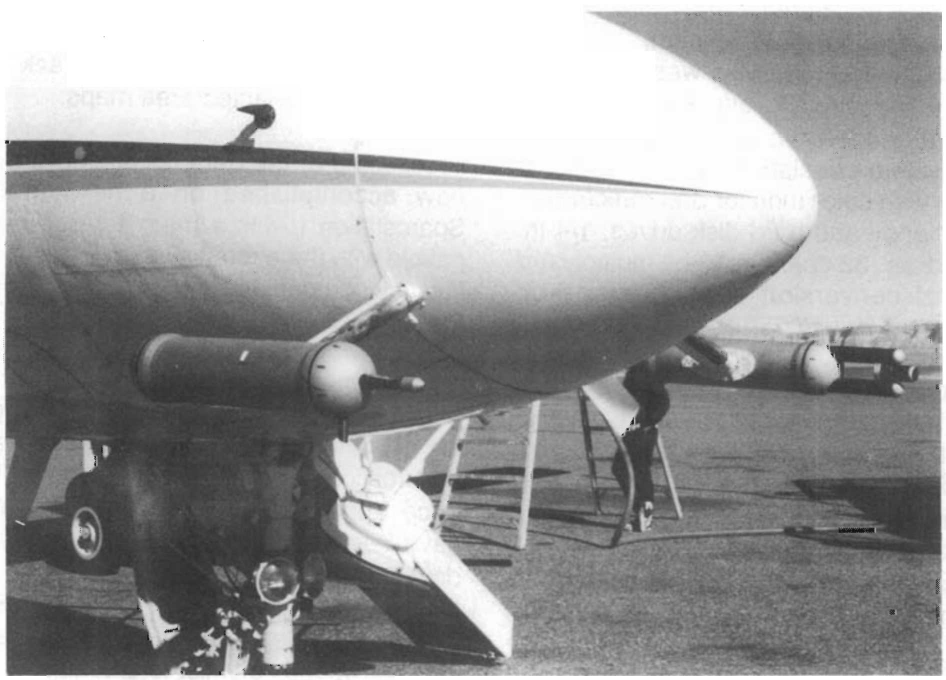

FIGURE 2. Spectrometer Probes Installation.

fuselage area to accommodate the manually deployed collectors and project them further above the fuselage top into the free airstream. Dummy cores are installed in the housings when collectors are not in use.

A specialized sampling probe, denoted the Counterflow Virtual Impactor (CVI), was constructed for PNL and installed on the G-1 by personnel from the University of Washington. A theoretical discourse can be found in the paper by Ogren et al. (1985). Briefly, cloud droplets are separated from interstitial gases, particles, and raindrops by an air counterflow outward in the probe, which is adjusted to set the size of droplets that are allowed to enter the probe. The droplets are evaporated, and the remaining trace gases and residual aerosol can be analyzed by various in situ instruments.

In FY 1990, a preliminary study was completed by the Battelle Columbus Laboratory to determine the feasibility of installing a Trace Atmospheric Gas Analyzer (TAGA)[a] in the G-1. The TAGA is a triple quadrupole mass spectrometer capable of measuring a broad spectrum of atmospheric trace constituents at very low (ppb and ppt) concentrations and with high specificity. It is a relatively large laboratory-bound apparatus in its current state. In October 1987, however, the TAGA was installed in the PNL DC-3 aircraft and successfully test flown. Objectives of the recent investigation were to redesign the physical packaging of the TAGA to permit entry and installation on the G-1, analyze aircraft vibration as input to the development of shock protection schemes, determine electrical power and weight distribution requirements, and consider modifications to the aircraft data system for data acquisition and TAGA control. The study concluded that the G-1/TAGA merger can be successfully accomplished, and it is planned to complete physical installation and testing in FY 1991. Airborne implementation of the TAGA will permit measurements of key atmospheric trace compounds over broad geographic and vertical domains at sensitivities previously unattainable.

(a) Sciex, Thornhill, Ontario, Canada.

References

Busness, K. M., and J. M. Hales. 1988. "PNL Research Aircraft Activities." In *Pacific Northwest Laboratory Annual Report for 1987 to the DOE Office of Energy Research, Part 3, Atmospheric Sciences*, pp. 75-76. PNL-6500 Pt 3, Pacific Northwest Laboratory, Richland, Washington.

Busness, K. M. 1989. "Development of the G-1 Research Aircraft." In *Pacific Northwest Laboratory Annual Report for 1988 to the DOE Office of Energy Research, Part 3, Atmospheric Sciences*, pp. 48-52. PNL-6800 Pt 3, Pacific Northwest Laboratory, Richland, Washington.

Busness, K. M., M. Terry Dana, W. E. Davis, D. W. Glover, R. V. Hannigan, R. N. Lee, D. J. Luecken, J. M. Thorp, and S. D. Tomich. 1990. "Overview of the Frontal Boundary Study." In *Pacific Northwest Laboratory Annual Report for 1989 to the DOE Office of Energy Research, Part 3, Atmospheric Sciences*, pp. 24-26. PNL-7200 Pt 3, Pacific Northwest Laboratory, Richland, Washington.

Huebert, B. J., S. Vanbramer, and K. L. Tschudy. 1988. "Liquid Cloudwater Collection Using Modified Mohnen Slotted Rods." *Journal of Atmospheric Chemistry* 6:252-263.

Ogren, J. A., J. Heintzenberg, and R. J. Charleson. 1985. "In-Situ Sampling of Clouds With a Droplet to Aerosol Converter." *Geophysical Research Letters* 12(3):121-124.

Winters, W., A. Hogan, V. Mohnen, and S. Barnard. 1979. "ASRC Airborne Cloud Water Collection System." *ASRC-SUNYA Publication No. 728*, Albany, New York.

Climate
Research

CLIMATE RESEARCH

Climate change research at PNL, like other research efforts aimed at this complex issue, is examining the fundamental processes that control climate systems. The intent of our studies is to reduce serious uncertainties that prevent accurate predictions of climate change and its effects. The program aims to improve data collection and interpretation methods as well as model components and parameterizations so that we may ultimately link observed climate changes to the predictions from the greenhouse hypothesis. Our approach includes the development of a scientific information base and tools for analyzing the implications of anthropogenic emissions on the Earth's climate. Three areas of research are reported: atmospheric radiation, ocean-atmosphere interactions, and source and resource analysis.

PNL is responsible for coordinating and integrating the field and laboratory measurement programs, modeling studies, and data analysis activities of a new research program in FY 1990 on global change. The Atmospheric Radiation Measurements (ARM) program will increase the reliability of predicting regional and global changes in climate in response to increasing atmospheric concentrations of greenhouse gases including CO_2. Improvements in the treatment of radiative transfer in general circulation models (GCMs) under clear sky, broken cloud, and general overcast conditions and in the parameterization of cloud properties, cloud formation, and cloud maintenance in GCMs are the objectives of the multilaboratory effort being led by PNL.

Ocean research related to climate change is examining ocean-atmosphere interaction, ocean circulation and climate modeling, and ocean measurements technology. The program is conducting experimental studies and modeling exchange processes at the air-sea interface for heat, CO_2, and other radiatively active gases. Physical, chemical, and biological processes involved in transfer mechanisms at the sea surface, such as bubble plumes and surface microlayer films, are being studied experimentally. Ocean dynamics that transport and redistribute heat and gases captured at the surface are also not well understood; consequently, parameterizations must be improved to adequately describe the dynamics of the surface mixed layer, transport through the thermocline, and formation of deep water.

Research in greenhouse gas emissions is under way to improve the reliability of forecasted emissions of CO_2 and other radiatively active gases. Model development, validation, and uncertainty evaluations depend on improved and expanded data bases, including more definitive information on energy production and consumption practices. The changing technologies and policies of the United States and other countries must be analyzed to anticipate contributions to future emissions of greenhouse gases and their effects on society, particularly on a regional basis.

The regional impacts of CO_2 increases are also being analyzed. Methods are being developed and implemented for analyzing the impacts of climate change and CO_2 increases on natural resources and society at the regional level. Data are being gathered and examined on climatic, environmental, and societal characteristics for a selected region of the United States, and approaches are being developed for predicting the consequences of CO_2/climate change for natural, biological, and human resources.

The progress described in the following articles was supported by the following research tasks:

- **Atmospheric Radiation Measurements**
- **CO_2 Ocean Research**
- **Resource Analysis Research.**

The Atmospheric Radiation Measurement (ARM) Program: A Study of Radiation Forcing and Feedbacks

G. M. Stokes

With the assistance of PNL, DOE has created a major new program to reduce the uncertainties found in models of the earth climate due to the effects of clouds and radiation (DOE 1990). The ARM Program is a direct continuation of DOE's decade-long effort to improve GCMs and related models for providing reliable simulations of regional and long-term climate change in response to increasing atmospheric concentrations of greenhouse gases. The objective of the ARM Program is to provide an experimental testbed for the study of important atmospheric effects, particularly cloud and radiative processes, and to test parameterizations of these processes for use in GCMs. This effort will support the continued and rapid improvement of GCM predictive capability on regional and global scales.

Over the past 10 years, the research programs of DOE and other agencies have made significant progress toward understanding the potential for global climate change and the resulting consequences. Models of the global climate system have advanced to include realistic geography, the annual cycle of the seasons, and varying cloud cover. However, this decade of research has also revealed that considerable uncertainties in model estimates remain. For example, although the 1980s have been especially warm, the extent of global warming over the past century estimated by current models may have been two to three times greater than what has occurred. Further, when the results of different models are compared, there are substantial differences, particularly on a regional level, among their estimates of temperature and precipitation changes in response to doubled CO_2 (Luther et al. 1988; Cess et al. 1989). Therefore, we do not know with sufficient accuracy how large the climatic changes will be, how rapidly the changes will occur, or how the changes will be distributed over the globe (Gates 1987; Wang et al. 1988).

Changes in cloud cover and cloud characteristics, because of their intimate relationship with infrared and solar radiation, are a major factor in determining the magnitude of potential warming resulting from increased atmospheric concentrations of greenhouse gases. Also, the accuracy of radiative calculations, including the treatment of clouds, affects the accuracy of estimates of climate sensitivity. Together, clouds and radiative transfer control the radiative forcing that drives some of the key feedbacks of the global climate system. Thus, to gain the needed improvements in GCMs, the interagency Committee on Earth and Environmental Sciences (CEES 1990) has identified cloud-climate interactions as the highest research priority within the U.S. global change research program.

The following scientific requirements emerge as the most critical for a program designed to remedy key weaknesses of current models:

- Field measurements of the vertical profile of the spectral radiative energy balance under a wide range of meteorological conditions must be quantified at a level consistent with climatologically significant energy flows of 1 to 2 W m^{-2}.
- The processes controlling the radiative balance must be identified and investigated. Our understanding of these processes must be validated by a direct and comprehensive comparison of field observations with detailed calculations of the radiation field and associated cloud and aerosol interactions.
- Improved parameterizations of the radiative properties of the atmosphere as used in GCMs must be based on intensive measurements at a variety of temporal and physical scales. A major emphasis must be placed on the role of clouds, including their distribution and microphysical properties.

Within this framework of scientific requirements, the goals of the ARM Program are twofold. First, it will attempt to improve the treatment of radiative transfer in GCMs and related models for clear sky, general overcast, and broken cloud cases. Second, it will provide a testbed for cloud parameterizations used in climate models. Measures of the quality of the models will include their ability to reproduce observed wavelength and direction-dependent fluxes of longwave and shortwave radiation and the time-varying distribution of cloud type and amount.

Experimental Approach and Configuration

ARM is an observational program driven by theoretical and modeling requirements. The ARM Program will provide data to improve and test the GCM parameterizations of clouds, their microphysical composition, and their effects on radiative forcing. It is designed to support the testing of a variety of radiative and cloud process models with a broad range of observations and to meet the measurement requirements of a variety of research teams with the same basic data streams. Measurements from the ARM Program will help to improve the accuracy and predictive capability of GCMs, which are currently the best scientific tools available for estimating global climate change and its regional distribution.

The observational component of ARM will consist of coordinated sets of instruments at each of four to six sites. Each ARM site will have three closely associated components: a central site, a three-dimensional mapping network surrounding the central site, and an extended observing network. Observations at the central site will detail the radiative and meteorological characteristics of the atmospheric column above the site using profiling and high spectral resolution radiometric instruments. The mapping network is designed to measure the three-dimensional structure of the atmosphere near the central site. The extended observing network will include 16 to 25 sets of instrumentation that are geographically distributed to provide critical data for understanding how to generalize the measurements at the central site to the 200 x 200 km grid size of future GCMs. Figure 1 shows an artist's conception of an ARM site.

In addition to the permanently placed equipment at the central and extended sites, ARM will maintain a mobile version of the basic experimental equipment found at the central site and additional instrumentation for use in special measurement campaigns. Also, despite the recent advances in remote sensing technology, ground-based remote sensing instrumentation alone cannot meet all of the observational requirements of ARM. As a result both aircraft and satellite observations will play an important role in the experimental strategy. Aircraft will be used to profile the radiation field as a function of altitude, to calibrate remote sensing systems, and to directly sample key atmospheric constituents in support of intensive measurement campaigns. Satellite observations of radiative fluxes at the top of the atmosphere and profiles of atmospheric conditions in regions beyond the range of sondes and ground based sensors will be crucial to ARM.

Organization of ARM Program

The ARM Program is managed through the ARM Project Office at PNL and consists of three other distinct entities: the Science Team, the Instrument Development Program, and the Clouds and Radiation Testbed (CART). The Project Office has three major functions: provide central planning and management for the ARM Program, support activities of the DOE/OHER Atmospheric and Climate Research Division, and coordinate ARM Program activities with related technical activities in other federal and international agencies.

The responsibilities of the Science Team are to conduct approved research projects, provide basic guidance for the design of modeling studies and the selection of sites and instruments, and set the scientific direction of the ARM Program.

The Instrument Development Program provides two levels of instrument development within ARM. First, it supports the long-term development of critical, high-risk technologies which will be of long-term benefit to ARM. Second, directed instrument development is supported to meet, on short notice, a measurement need within ARM that cannot be met by other means.

CART, the basic experimental infrastructure for the ARM Program, consists of several basic elements: several permanent observing sites, a mobile measurement capability, an ability to support intensive measurement campaigns either in support of a central ARM site or in collaboration with related programs, and a data system that supports the acquisition, visualization, and analysis needs of the Science Team. Several interlaboratory teams contribute to the CART: site selection, instrumentation, site operations, modeling, and data systems. Each team is headed by a principal investigator from one of DOE's national laboratories.

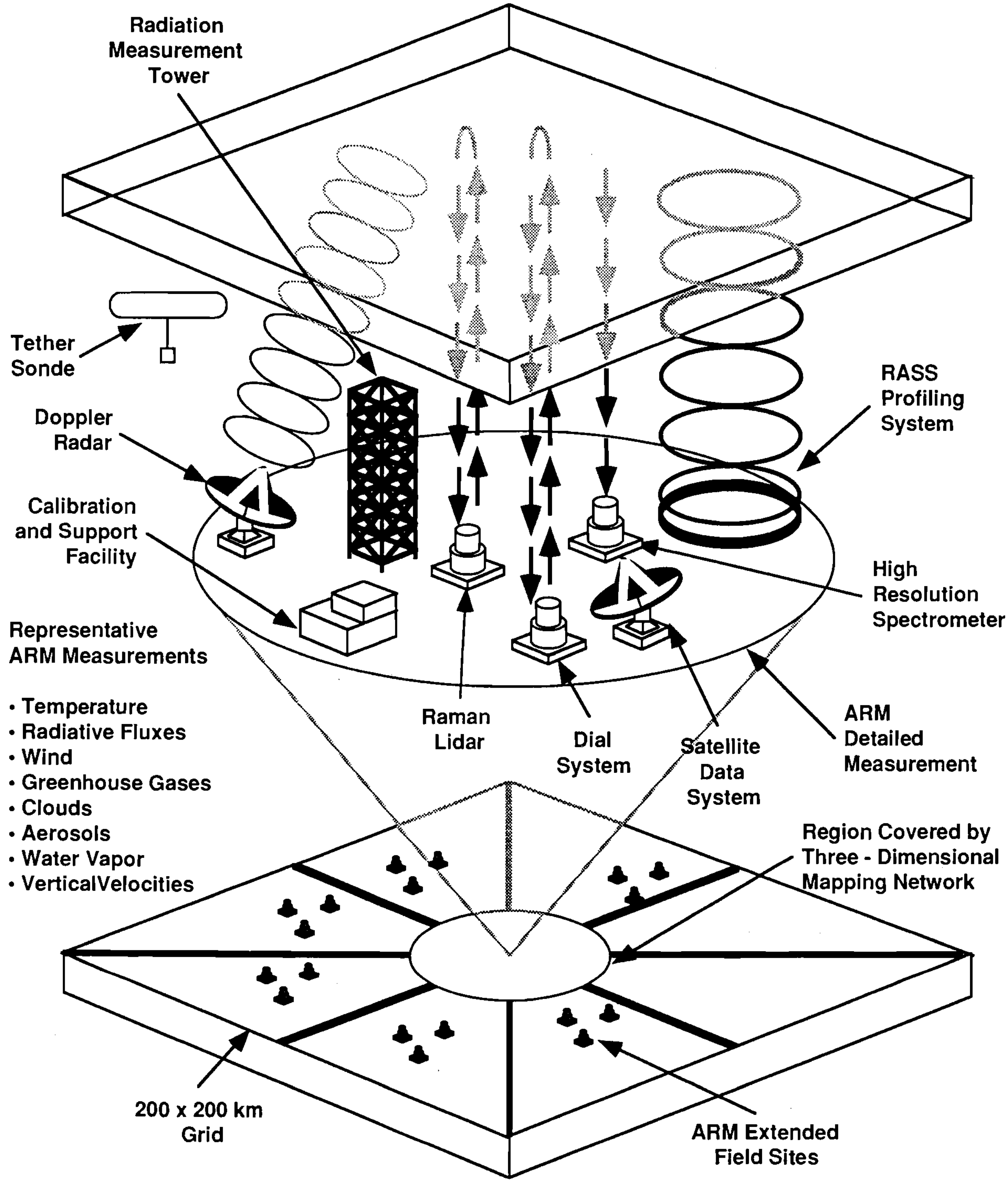

FIGURE 1. The ARM Experimental Configuration.

Accomplishments

The initial program plan for ARM, completed in 1990, outlines the classes of observational tools required to meet the program's observational objectives. The instrumentation is undergoing extensive review in light of the detailed experimental requirements specified by the individual ARM investigators. Pilot observational programs, initiated in late 1990, will continue through early 1991. These observational campaigns are being supported by sensitivity studies of models conducted during the same period. The data system for ARM is in the design phase; the conceptual design was reviewed twice during the summer of 1990. The Science Team for the program was selected during the summer of 1990 based on peer-reviewed proposals; the team convened for the first time in November 1990. The ARM Program currently supports work at 15 universities, 7 of DOE's national laboratories, 5 other agencies, and several private industries.

The site selection team has recommended a set of geographical regions, or locales, for ARM sites and is preparing a report describing the process and rationale for their recommendations. The locales are ordered according to the scientific understanding expected to be gained by conducting ARM measurements in these locales and by logistical considerations for operating sites in these locales. The five primary locales recommended for long-term occupancy (7 to 10 years) are

1. Southern U.S. Great Plains
2. Eastern North Pacific Ocean
3. Tropical Western Pacific Ocean or Australia-Indonesia Semi-enclosed Sea
4. North Slope of Alaska
5. Gulf Stream off Eastern North America, extending eastward.

In addition to these primary locales, the following supplementary locales were recommended for short-term or campaign occupancy to study processes unique to such locales or to take advantage of other projects that are synergistic with ARM:

1. Central Australia or Sonoran Desert
2. Northwest U.S.-Southwest Canada Coast
3. Amazon Basin or Congo Basin
4. Beaufort Sea, Bering Sea, or Greenland Sea
5. Eastern Atlantic Ocean, Azores to Africa.

The locations of the recommended locales are shown in Figure 2. Current plans call for initial occupation of the first ARM site in 1992.

Through this highly focused, long-term observational and analytical research effort the ARM Program will accelerate improvements in both observational methodology and GCMs. The ARM Program will enable DOE to continue to collaborate extensively with existing global change research programs at other agencies, including the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA).

References

Cess, R. D., et al. 1989. "Interpretation of Cloud-Climate Feedback as Produced by 14 Atmospheric General Circulation Models." *Science* 245:513-516.

The Committee on Earth and Environmental Sciences (CEES). 1990. *Our Changing Planet: The FY 1991 U.S. Global Change Research Program*. The Committee On Earth Sciences, Washington, D.C.

U.S. Department of Energy (DOE). 1990. *Atmospheric Radiation Measurement Program Plan*. DOE/ER-0441, U.S. Department of Energy, Washington, D.C.

Gates, L. W. 1987. "Problems and Prospects in Climate Modeling." In *Toward Understanding Climate Change*, ed. U. Radok, pp. 5-34. Westview Press, Boulder, Colorado.

Luther, F. A., R. G. Ellingson, Y. Fouquart, S. Fels, N. A. Scott, and W. J. Wiscombe. 1988. "Intercomparison of Radiation Codes in Climate Models (ICRCCM): Longwave Clear-Sky Results--A Workshop Summary." *American Meteorological Society Bulletin* 69:40-48.

Wang, W. C., et al. 1988. *Surface Energy Balance of Three General Circulation Models: Current Climate and Response to Increasing Atmospheric* CO_2. Technical Report DOE/ER/60422-H1, U.S. Department of Energy, Washington, D.C.

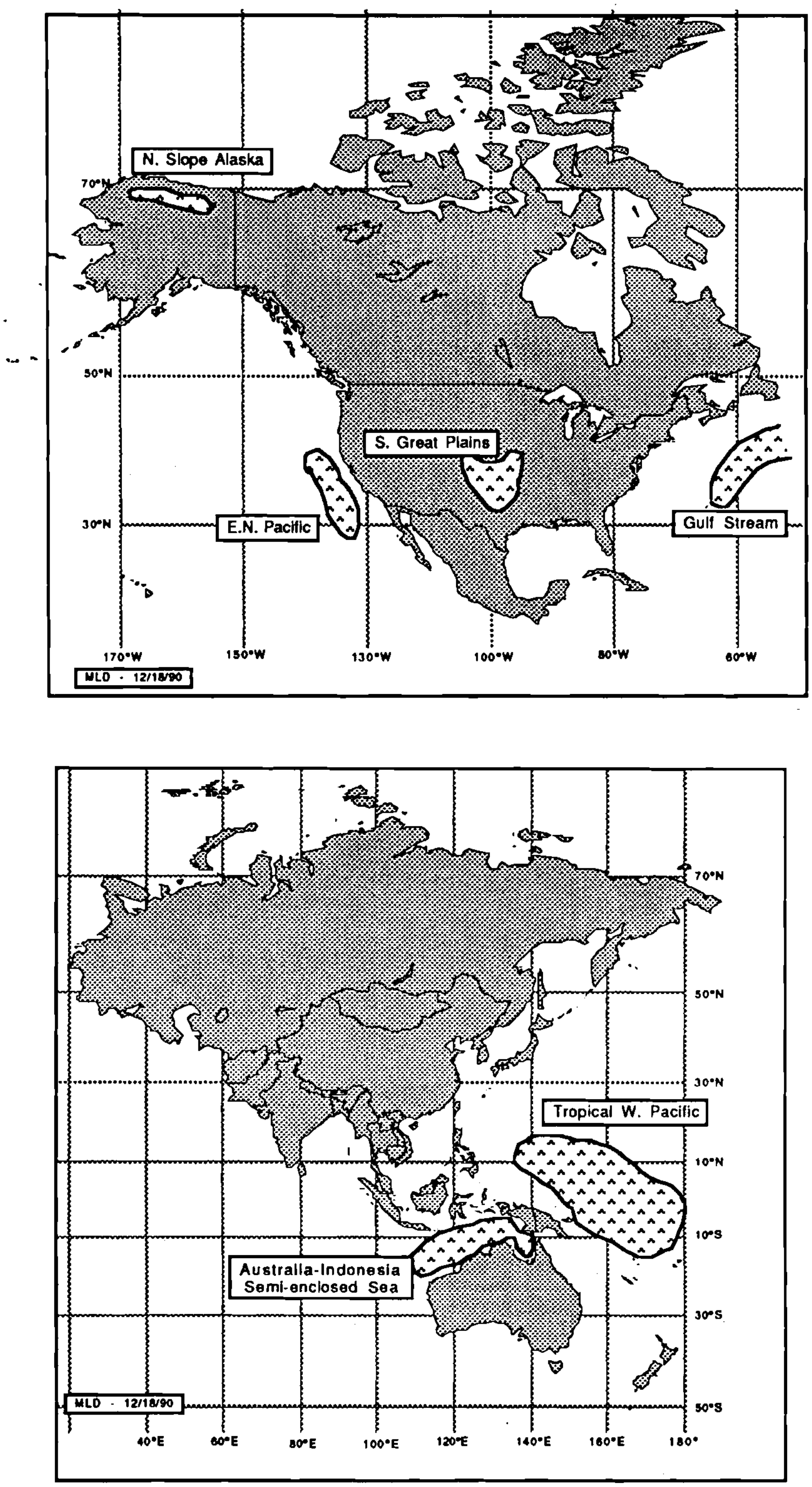

FIGURE 2. CART Primary Locales.

Carbon Dioxide Ocean Research

J. P. Downing, W. E. Asher, D. W. Denbo, E. D. Skyllingstad, and M. C. Richmond

The objective of the CO_2 Ocean Research project is to improve understanding of the role of the ocean in CO_2-induced climate change. Staff at both PNL and the Battelle/Marine Sciences Laboratory (Battelle/MSL) provide technical support to ACRD and conduct research in the following ongoing tasks: exchange of CO_2 at the air-sea interface, deep water formation in ocean general circulation models, and surface-layer processes, including air-sea exchanges of mass, heat, and momentum. Direct support to ACRD includes development of aqueous CO_2 standards and administration of the science team for the Global Survey of CO_2 in the Oceans (SRGP 89-7). These activities are conducted in anticipation of large, multiagency ocean observations to be conducted in the 1990s, such as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS).

For the CO_2 Ocean Research project, FY 1990 progress included further study, including laboratory experiments, of the relationship of ocean whitecap coverage to the air-sea exchange of CO_2, the continued study of ocean deep convection and the development of a two-dimensional model of convection, and numerical experiments on ocean surface layer dynamics. In addition, the project oversaw the development of an advanced instrument for ocean measurements.

Effects of Breaking Waves and Whitecaps on CO_2 Exchange

Models of the global ocean carbon cycle that include a parameterization of air/sea exchange processes are being developed to calculate the uptake of CO_2 by the ocean. Because breaking waves are believed to increase the flux of gases across the air/sea interface, research is under way to correlate air/sea gas transport velocities, k_L, with whitecap coverage, F_c. Correlation of these terms may allow the prediction of k_L from remote (i.e., satellite) measurements of apparent microwave brightness temperature because breaking waves are also known to increase sea surface microwave emissivity.

An initial step in developing this remote-sensing based method for predicting air/sea gas transport velocities was the design and construction of the Battelle/MSL Whitecap Simulation Tank (WST). Development of the WST and results of preliminary experiments were reported by Asher et al. (1990a) in last year's annual report. This year, further experiments to measure the air/gas transport velocities of CO_2, O_2, DMS, SF_6, and He were conducted in the WST. The WST facility was expanded and additional equipment was installed. Also, a field experiment, conducted in April 1990 on Georges Bank in the Atlantic Ocean, provided data for validating the WST observations.

A schematic of the WST is shown in Figure 1. The laboratory experiments conducted in the WST this year were

- measurement of oxygen evasion and invasion rates for sea water and fresh water. We are studying the effects of temperature on bubble plume governed gas exchange.
- measurement of evasion rates in sea water for the radiatively important trace gas dimethyl sulfide (DMS). The DMS experiments were in collaboration with T. S. Bates of NOAA/PMEL.
- measurement of evasion rates for DMS and SF_6 in sea water and fresh water. These experiments were collaborative with R. Wanninkhof of Lamont-Doherty Geological Observatory.

Expansions to the WST air/sea gas exchange experiments included

- constructing a second whitecap simulation tank with constant temperature capability
- acquiring a phased Doppler anemometer for simultaneous measurement of bubble size distributions and turbulence velocities
- acquiring a surplus portable gas chromatograph equipped with a thermal conductivity detector for He, SF_6, and N_2O measurements.

Parameterizations of k_L in terms of F_c developed using the WST data must be validated through field experiments. To this end, in April 1990 the MSL conducted a whitecap/dual tracer gas exchange experiment on Georges Bank. This effort was in collaboration with R. Wanninkhof (LDGO) and E. C. Monahan (University of Connecticut).

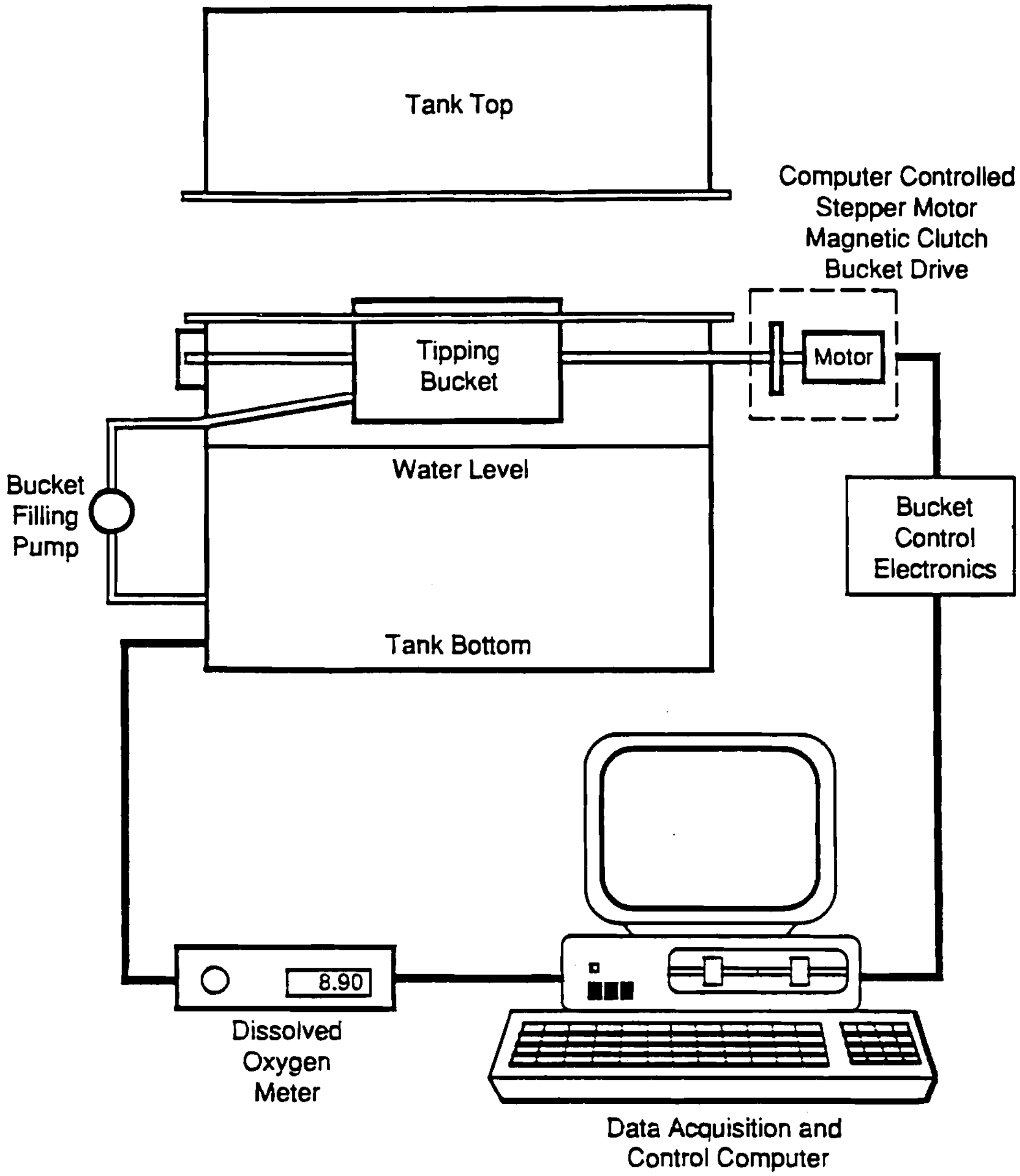

FIGURE 1. Schematic Diagram of Whitecap Simulation Tank.

This year's research activities yielded encouraging results (Asher et al. 1990b). From the WST experiments, we have developed an empirical relationship between k_L and F_c as a function of Schmidt number. Figure 2 plots k_L predicted using the model versus k_L measured in the WST. Excellent correlation is observed for a wide range of Schmidt numbers and aqueous phase solubilities.

The Georges Bank experiment represents the first in situ concurrent measurement of air/sea gas transport velocities and whitecap coverage. The field data, which should be available in early 1991, will be used to test the empirical parameterization developed using the WST data.

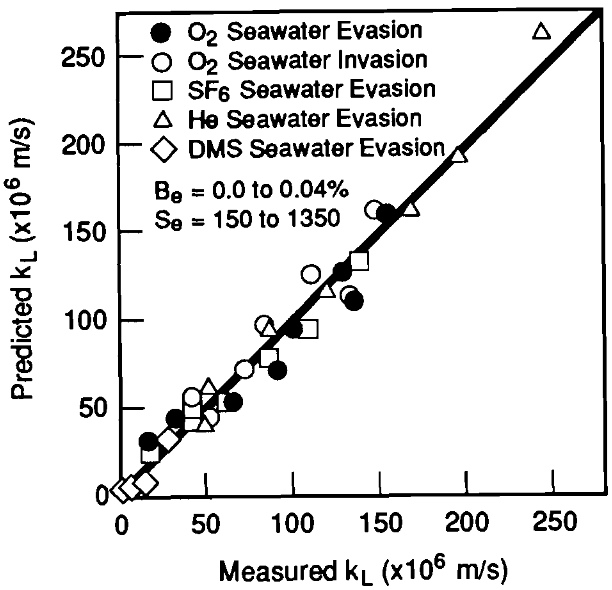

FIGURE 2. Predicted Versus Measured k_L. The ordinate is k_L predicted for He, SF_6, O_2, and DMS by the empirical relationship

$$k_L = 0.078 S_c^{-1/2} + F_c (27.3 S_c^{-2/3} - 0.078 S_c^{-1/2})$$

where S_c is the Schmidt number of the gas and F_c is the fractional area bubble plume coverage in the WST. The absicssa is k_L measured in the WST for the same gas with the same F_c. The empirical relationship demonstrates that the presence of bubbles changes the S_c dependence of k_L in accordance with conceptual models of bubble plum governed gas transport.

This research is a collaborative effort between the National Oceanic and Atmospheric Administration/ PMEL in Seattle, Washington; the Lamont-Doherty Geological Observatory in Palisades, New York; the Marine Sciences Institute, University of Connecticut-Avery Point, Groton, Connecticut; and the National Atmospheric and Space Administration-Goddard Space Flight Center.

Development of Oceanic Deep Convection Models for Climate Research

Deep convection is an important process in the climate system. Accordingly, the CO_2 Ocean Research program includes an effort to design and test a numerical model of open water oceanic deep convection and apply the model to the development of improved parameterizations of deep convection in ocean general circulation models. The modeling program and initial results were described in last year's annual report by Skyllingstad (1990). Research is proceeding on two fronts: 1) analysis of data from the World Ocean Circulation Experiment's Community Modeling Effort (CME) and 2) the development of an ocean convection model.

Analysis of CME Data

Five years of 3-day CME simulation data were converted to 30-day averages and standard deviations. A preliminary analysis of the data was presented at the Monterey Workshop on Deep Convection (Skyllingstad et al. 1990) and was accepted as a section in an upcoming book on deep convection.

Several conclusions that can be drawn from the analysis of CME data are

- The deep current around Greenland that transports Denmark Strait Overflow Water is not produced by the CME model.
- The shallow current that normally follows the East Greenland coast around the Labrador Sea flows straight across the Labrador Sea at 60°N.
- Convection occurs over an unrealistically large region of the Labrador Sea, does not penetrate below 700 m, and occurs during the summer.

Example comparisons of the CME results with observations are shown in Figures 3 and 4. Figure 3 shows a time history of the density profile from the model and from Ocean Weather Ship Bravo (Lazier 1980). Although the model annual cycle is surprisingly similar to observations, below 700 m the computed density is much more uniform than was observed from 1964 to 1973. The plots also show that the CME model does not convect deep enough in the winter.

Figure 4 presents a modeled and observed cross section from Cape Farewell at the southern tip of Greenland to the Flemish Cap, off the coast of Newfoundland. A comparison of these plots shows that the CME model does produce the proper temperature and salinity structure in the deep water south of Greenland. Cold, saline water is observed near the shelf (left side of profiles), where the Denmark Strait Overflow enters the Labrador Sea. These features are completely missing in the CME data.

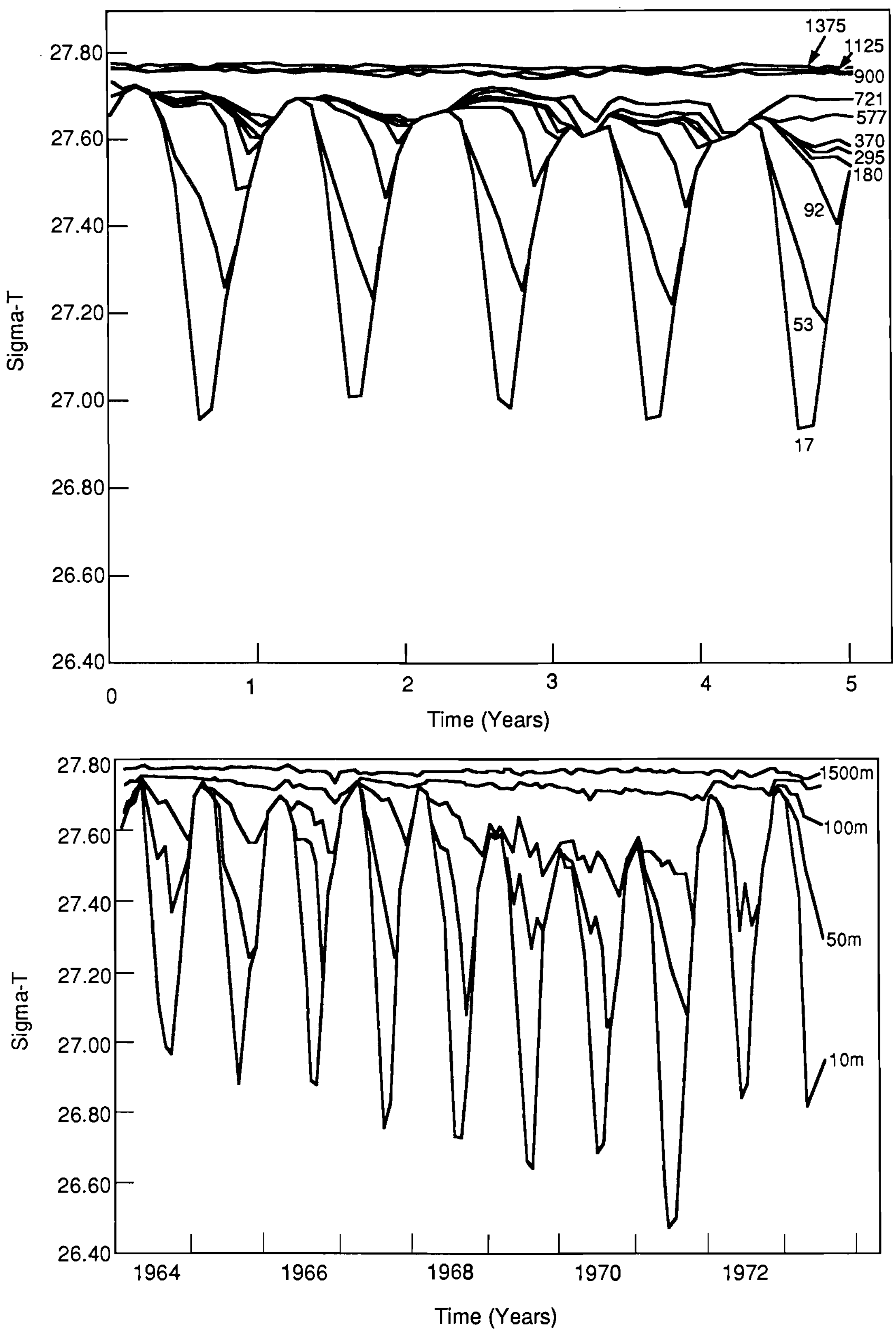

FIGURE 3. Density Structure Versus Time at Depths from 10 to 1500 m from the CME Model (top) and Ocean Weather Ship Bravo (bottom).

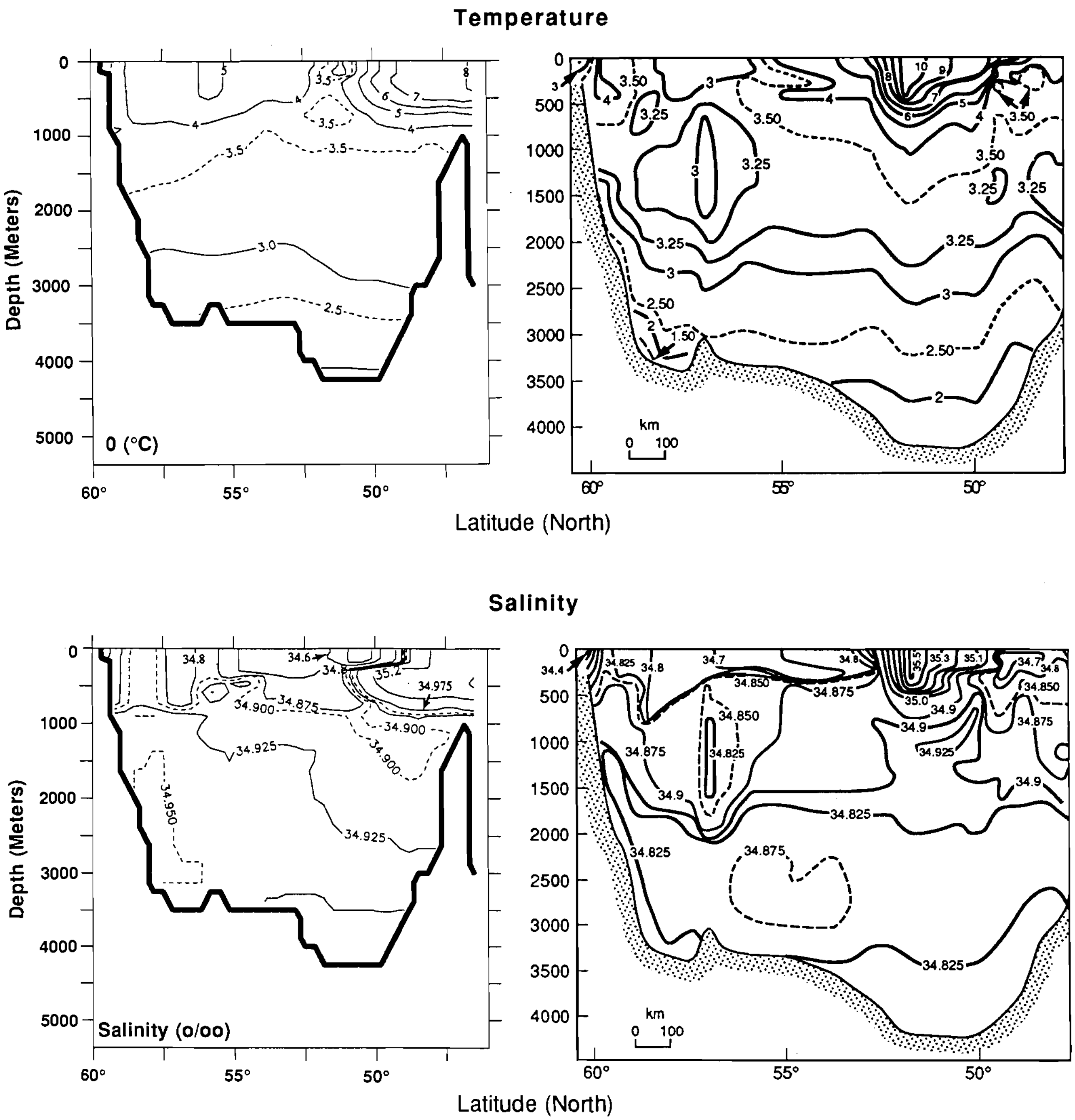

FIGURE 4. Temperature (top) and Salinity (bottom) Cross Sections from Cape Farewell to Flemish Cap (46°30'W) from the CME Model (left) and Observations (right).

Development of Ocean Convection Model

In developing the ocean convection model (OCM), we have concentrated on the two-dimensional form of the basic equations. Initially, we adapted the non-hydrostatic atmospheric model used by Skyllingstad (1986) to the ocean by adding a diagnostic density field, a constant eddy diffusivity, and cyclic horizontal boundary conditions. We then added a lookup table for calculating density, a transport equation for salinity, and a Richardson-number-based vertical turbulent diffusion. Because seawater density behaves nonlinearly over oceanic ranges of pressure, temperature, and salinity, an accurate calculation of density is essential in convection studies. Sub-grid-scale advection and diffusion can be tracked in the model with conservative tracers using the positive definite transport algorithm of Smolarkiewicz (1983). We verified the model with idealized salinity and temperature profiles and with observed ones from the Southern Ocean.

Results from our current version of the two-dimensional OCM are qualitative because the model and turbulence parameterizations are simplified. The most significant outcome of the initial simulations concerns the relationship between sea water density and pressure: the thermobaric effect. We examined a case where the upper layer becomes unstable when strong vertical motions occur. This is like conditional instability in the atmosphere. After 72 h, eddies in the top 500 m break through the thermocline and initiate strong downwelling because of the thermobaric effect. The action of the eddies and downwelling produces a temperature and salinity minimum located in the model domain at a depth of 1250 m. At this depth, the density is stably stratified. Temperature and salinity inversions similar to those produced in the two-dimensional model have been observed in both the North Atlantic and in the Southern Ocean around Antarctica.

These similarities are a preliminary indication that our two-dimensional model is simulating deep oceanic convection correctly, although in a rudimentary way. We are sufficiently encouraged by the results to proceed with more systematic verification.

Ocean Surface Layer Dynamics

Study of ocean surface layer dynamics seeks to determine, by numerical experiments on surface-layer dynamics, if a more detailed treatment of surface-layer processes will substantively change climate and atmospheric CO_2 projections of simple mixed-layer models. The output of the task will be a numerical model of the turbulent dynamics of the surface mixed layer that will integrate existing field measurements and provide insight into the role of quantities that cannot be directly measured.

The primary goal is to design and construct a numerical model capable of simulating the three-dimensional turbulent dynamics of the ocean surface layer. Many questions remain unresolved because of the lack of direct measurements of key quantities (e.g., buoyancy and turbulent fluxes) and because of the inherent difficulties in separating the contributions of waves, current shear, and turbulence. A numerical approach is required because of the difficulties in sampling the upper 5 to 10 m of the ocean. Large-eddy-simulation (LES) techniques will be used to avoid the uncertainties introduced by typical turbulence closure models. The advantage of using an LES model is that most of the turbulent energy is carried by the resolved large-scale motions that are directly computed rather than parameterized. The motion of the free surface will be directly computed with the marker and cell method. The numerics will be tested with data from laboratory experiments and open ocean measurements.

The model will provide the means to study the complex, nonlinear interactions of organized Langmuir circulations, surface waves, and upper-ocean turbulence. Increased understanding of the detailed physics of these processes in the ocean mixed layer will lead to the improvement of mixed layer models that are incorporated into ocean general circulation models.

Instrument Development

To meet the pressing needs for synoptic information about the ocean for climate research, acoustic modeling, and physical characterization of the ocean environment, accurate expendable sensors are urgently needed. Battelle/MSL oceanographers and engineers worked with Ocean Sensors, Inc., of San Diego, California, to develop a prototype microcomputer-controlled, expendable device to measure ocean conductivity, temperature, and depth (CTD). The device, called an AXCTD, is designed to be deployed from ships or, with a parachute, from low-flying aircraft. The AXCTD records a CTD profile on descent, a time series while on the bottom, a profile on ascent, and then transmits surface observations while in a drifting mode. The AXCTD remains on the ocean bottom until a preprogrammed event directs it to jettison its ballast and rise to the surface. Ground positioning and data transmission are accomplished with an ARGOS satellite. The prototype development is to be followed by construction of an engineering model, and a contract for the engineering model development is under solicitation.

References

Asher, W. E. , E. A. Crecelius, J. P. Downing, and E. C. Monahan. 1990a. "Experiments on the Influence of Whitecaps on Air/Sea Gas Transport Rates." In *Pacific Northwest Laboratory Annual Report for 1989 to the DOE Office of Energy Research: Part 3. Atmospheric Sciences*, PNL-7200 Pt. 3, Pacific Northwest Laboratory, Richland, Washington.

Asher, W. E., E. C. Monahan, R. Wanninkhof, and T. S. Bates. 1990b. "Correlation of Fractional Foam Coverage with Gas Transport Rates." Paper presented at the Second International Symposium on Gas Transfer at Water Surfaces, Minneapolis, Minnesota, September 10-14, 1990.

Lazier, J.R.N. 1980. "Oceanographic Conditions at Ocean Weather Ship Bravo, 1964-1974." *Atmosphere-Ocean* 18:227-238.

Skyllingstad, E. D. 1986. "The Effects of Stratification and Vertical Wind Shear on Atmospheric Solitary and Cnoidal Gravity Waves: A Numerical Investigation." Ph.D Thesis, University of Wisconsin, Madison, Wisconsin.

Skyllingstad, E. D. 1990. "A Preliminary Analysis of Deep Convection in an Ocean General Circulation Model." In *Pacific Northwest Laboratory Annual Report for 1989 to the DOE Office of Energy Research: Part 3. Atmospheric Sciences*, PNL-7200 Pt. 3, Pacific Northwest Laboratory, Richland, Washington.

Skyllingstad, E. D., D. W. Denbo, and J. P. Downing. 1990. "Convection in the Labrador Sea: Community Model Effort (CME) Results." In *Monterey Workshop Deep Convection*. Elsevier Publishers, The Netherlands.

Smolarkiewicz, P. K. 1983. "A Simple Positive Definite Advection Scheme with Small Implicit Diffusion." *Mon. Wea. Rev.* 111:479-486.

Special Research Grants Program (SRGP) 89-7. August 1989. *Federal Register.*

Progress Report on the Second Generation Model FY 1990

J. A. Edmonds

PNL has embarked on a program to develop a second generation model (SGM) of long-term, global greenhouse gas emissions. This modeling work grows out of the previous endeavors by PNL staff, who developed the long-term, global, energy-economic model of CO_2 emissions sometimes referred to as the Edmonds-Reilly Model (ERM). The ERM was a member of the first generation of long-term, global greenhouse gas emissions models. However, the ERM addressed only the energy-related greenhouse gases. The SGM responds to the expanded research needs for a model capable of assessing the interactions of the fully array of human activities and their consequences for the full array of greenhouse gas emissions. The principal design features of the SGM model are

- global coverage
- multiple greenhouse gases (CO_2, CH_4, CO, N_2O, NO_x, VOCs and CFC)
- general equilibrium analytical structure
- disaggregated human activities (agriculture, energy, transportation, manufacture, services)
- economic resources (land, labor, and capital)
- economic decision makers (households, government, and producers)

- capital stocks (by vintage of installation, and economic retirement, and retrofit of existing stocks)
- interactions between managed and unmanaged ecosystems
- multiple regions with key countries disaggregated
- international trade in goods, services, and capital
- 5-year time steps
- 2100 forecast horizon.

A graphical representation of the model is shown in Figure 1.

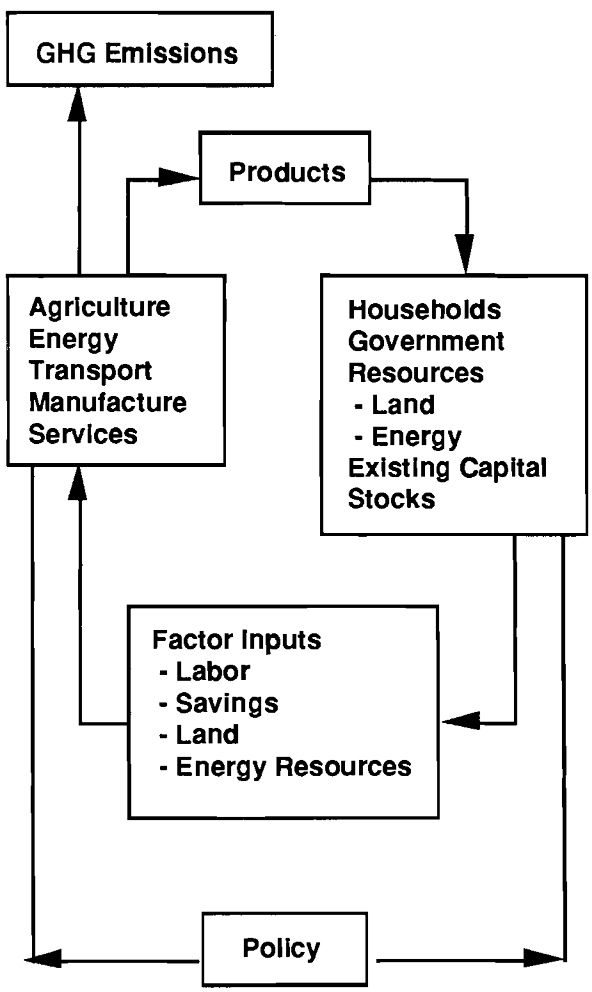

FIGURE 1. Simple Representation of the SGM.

During FY 1990, work was focused in two areas: 1) the **Capital Module**, which developed the relationship between technology availability and technology deployment within the context of a hierarchical modeling framework, and 2) the development of a **Generalizable Economy Description**, which can be used to characterize market, planned, and transitional economies. The capital module describes the relationship between future expectations, savings, investment, technology selection and penetration, and decisions regarding the retirement, idling, and employment of capital stocks.

Two visiting scholars, Igor Bashmakov, the Moscow Energy Research Institute, and Zhou Dadi, the Beijing Energy Research Institute, worked as part of the SGM team. Igor Bashmakov worked to develop a global energy data base and a description of Soviet decision making. Zhou Dadi worked to develop a behavioral description of Chinese decision making. Those economies, a mixture of planned and market economies even before the most recent changes, present an important source of information regarding the behavior of planned, market, and transition economies.

The model itself has been laid out as a series of interactive modules which exchange information with each other. Model development will be accelerated during the next year. The modeling team will be expanded to include a new team leader, and an assistant researcher. During FY 1991 a French visiting scholar, Richard Baron, is expected to join the team in February 1991 to assist in developing the model.

The Resources Analysis Research Project: A Methodology for Assessing Regional Economic Impacts of and Responses to Climate Change–the MINK Study

M. J. Scott

Global circulation models (GCMs) indicate that man-caused increases in greenhouse gases may elevate the average temperature of the Earth's atmosphere during the next century to levels not experienced in the last 100,000 years. A question that has received relatively little systemic attention is this: what are the consequences for human and natural systems, especially in view of human adaptation? The Resources Analysis Project has sought to improve the methods by which we assess the effects of climate change at the regional level. The study has addressed the potential impacts of climate change in a region centered on the four states of Missouri, Iowa, Nebraska, and Kansas (MINK).

The MINK project focused on a real historical climate anomaly as an analog for future climate change and analyzed the interactions of all of the resources resident within the MINK region as they might evolve under current and changing CO_2/climate conditions over the next 50 years. The MINK region was chosen for its relatively simple natural-resource-based economy, spatially coherent climate, and availability of data on both the region's resources and a potentially meaningful climate change analog--the Dust Bowl decade of 1931-1940. During the 1930s the region's climate was, on average, about 0.9°C warmer than normal and also drier than normal. The analog climate was combined with an atmospheric concentration of CO_2 of 450 ppm, a plausible concentration for the early part of the next century and a concentration consistent with CO_2 *equivalent* doubling. The analog climate was compared with that of the period--1951-1980--defined by the World Meteorological Organization as "normal."

Program Findings

In the program's first year (FY 1989), analysis focused on two areas: 1) an economic and biophysical baseline description of the MINK region and 2) the initial development of models to address the four major natural resource sectors, their intersectoral biophysical and economic linkages, and economic sectors within the MINK region that support them. It was found that the economy of the MINK region was three to four times as specialized in agriculture as that of the United States (as measured by personal income) and was economically vulnerable to climate change. Over half of the region's manufacturing exports are agriculturally related. Roughly 30% of the region's export base is agricultural products and agriculturally related manufactured products. The intensive mining of ground water for irrigation (about half of all regional water withdrawals and over 80% of consumptive uses are in irrigation) and growing demand for surface water for recreation and wildlife (ranging from 34 to 90% of average flow under current climate in the region's various water supply subregions) likely will result in significant future water demand-supply imbalances and stress on water management institutions even in the absence of climate change. The baseline description of the energy sector concentrated on four weather-sensitive sources of energy demand (both electric and non-electric irrigation pumping, air conditioning, crop drying, and space heat), which together account for about 30% of all energy used in the region, and two indirect sources of energy demand (fertilizer application and pesticides).

During the second year (FY 1990), the computer models adapted for the MINK study were used to simulate the impacts of the 1930s analog climate change and increased atmospheric CO_2 on the four natural resource sectors and the MINK regional economy. This was done in four stages: 1) the analog climate change first was imposed on today's economy with mid-1980s technology and no adaptation by economic actors in the region; 2) today's economic system was then allowed to make low-cost adjustments to climate change and CO_2 fertilization effects were allowed to occur in the agriculture and forestry sectors; 3) future economic growth to 2030 was projected to occur without climate change; and 4) analog climate change, CO_2 fertilization, and technical adaptation were all added to the scenario, one at a time, and the implications for the region's economy analyzed.

The impacts of climate change on "typical" agricultural cropping systems were analyzed using a version of the Erosion-Production Impact Calculator (EPIC) computer code originally developed at Texas A&M University (Williams et al. 1984). The EPIC code was modified in two major ways for this study to incorporate the direct effects of CO_2 on crop growth: 1) An adjustment was made to the photosynthesis equations in the model based on empirical, species-specific response surfaces for net photosynthesis as a joint function of irradiance and CO_2 concentration, expressed as radiation use efficiency (RUE). RUE is further adjusted for photosynthetic sensitivity to humidity for each species. 2) The Penman-Monteith (P-M) method of calculating evapotranspiration was incorporated in the model (see Martin et al. 1989). Net farm yields and profitability were estimated for over 40 "typical" prototype farms in the MINK region. Prototypes were developed from extensive interviews with agricultural experts in the region.

Preliminary results for the value of farm production appear in Table 1. These results assume that farmers make some low-cost attempts to minimize the effects of climate change by adjusting farming practices in the short run and that they adopt a reasonable range of new technologies in the long run.

Responses that were analyzed included changes in land management practices such as changes in crop selection and planting practices (dates, depths, spacing, sequences, and patterns), changes in irrigation practices (events, amounts, installation, or dismantling) and changes in harvest practices (timing and drying) (Easterling et al. 1989).

Analysis of water supplies and demand indicated that under the 1930s analog climate, average annual streamflows would decline to 72% of normal for the Missouri and Upper Mississippi basins and to about 93% of normal in the Arkansas basin, rendering streamflows inadequate to satisfy both consumptive and instream demand. At the same time, EPIC suggested that irrigation demand for water would rise sharply, increasing total consumptive use by 23% in the region if water use efficiency is not improved by increased CO_2 and by 17% if it is. Improved water conservation practices generally were not considered in the short run, but would clearly become much more important in the long run as navigation and hydroelectric power outputs of the Missouri main-stem dams are curtailed. A critical institutional issue in the context of climate change turned out to be the operating criteria of these dams. In the analysis of the effects on the regional economy, it was assumed that no additional water diversions for agriculture would be allowed. The resulting water shortages were modeled by reducing the acres in irrigated crops and watering these acres more intensively.

TABLE 1. Effects of Climate-Induced Reductions on Value of Crop Production in the MINK Regional Economy (million 1982$)

	1931-1940 Analog Climate		Analog Climate, CO_2, and Farmer Adjustments	
	Change	% Change	Change	% Change
1980s Conditions	-2709	-17.1	-532	-3.3
2030s Conditions	-5285	-22	+645	+3

The forest products resources of the MINK region were characterized and climate impacts were analyzed using a version of the FORET computer code (Solomon et al. 1984; Solomon and West 1987) called FORENA. FORENA was modified for the current project to allow for the possible effects of elevated atmospheric CO_2 concentrations on photosynthesis and water use efficiency. FORENA was used to perform preliminary analysis of forest stand biomass in stocked stands and after clearcutting at points up to 200 years in the future. Forests in southeastern Missouri (the only commercial forest area in the region) were found to be quite sensitive to increases in temperature and decreases in moisture. Within 10 years of imposing a 1930s analog climate, simulated biomass production declined between 7 and 20%. After 200 years, the analog climate resulted in a decrease of 25 to 60%. Elevated CO_2 reduced the losses slightly, but they were still 20 to 50% in the long term. Adaptation possibilities of the commercial forest products industry were found to be confined to salvage logging and early harvest. No analysis was done on the impact to values of standing forests such as tourism and recreation.

Regional energy demand and supply issues also were examined. In the absence of adaptation, the analog climate increased agricultural energy consumption by a net 3 to 4% (increases in irrigation demand for energy being partially offset by decreases in energy for crop drying). Reduced streamflow could impair cooling water condensing operations at thermal power plants, as well as reduce energy supplies from the six main-stem Missouri river dams. Analysis showed that energy used for irrigation pumping (most of it non-electric) under a 1931-1940 climate might increase by 23% if farmers simply were to try to replace moisture loss without any other adjustments. Although water temperatures would be higher and flows less under a warmer climate, analysis to date has not identified any major problems with supplies of water for energy within the region, since the major energy use of water (for power plant cooling) mainly represents a diversion rather than a consumptive use. Flows appear to be adequate for cooling for the region's power plants under reduced flows. Water for hydropower is not an issue in the region, contributing only about 3 to 6% of all electricity generated in the region. However, hydropower may become an issue in regions upstream on the Missouri River system.

Economic integration of the MINK region is being accomplished using the IMPLAN regional input-output model, originally developed for the U.S. Forest Service. During FY 1989, work focused on collecting economic data and describing the baseline economy so that the IMPLAN modeling system can analyze it. IMPLAN is a flexible modeling system based on a 500-plus sector national input-output table that can be adapted to any state or regional economy in the United States.

Table 2 shows the impacts of climate change on the MINK regional economy of changes in agricultural yields under today's technical and economic conditions for two alternative underlying assumptions. The first assumption is that the increases in costs of feedgrain (corn and sorghum) production lead to a reduction in export demand equal to the simulated decline in crop production from EPIC--i.e., the loss of production falls entirely on exports of crops from the region. This is a minimum damage case, since no downstream food processing industries are affected. Alternatively, in the maximum damage case, it is assumed that the full amount of the decline in feedgrain is borne by animal producers in the region, leading to a proportional decline in feedlots and meatpacking. Neither assumption is fully realistic; however, the two cases point out the range of possible effects.

TABLE 2. Effects of Climate-Induced Reductions in Feedgrains on Overall Regional Economic Production in MINK Under Mid-1980s Technical and Economic Conditions (million 1982$)

	1931-1940 Analog Climate		Analog Climate, CO_2, and Farmer Adjustments	
	Change	% Change	Change	% Change
Production Decline Falls on Exports	-3123	-1.0	-1777	-0.6
Production Decline Falls on Animal Producers in MINK	-29881	-9.7	-17622	-5.7

Within the resources available for the study, it proved too difficult to develop reliable production multipliers for the year 2030, so a complete analysis of the effects of lost production on the region could not be done for that year. However, comparing the crop production declines for the mid-1980s and 2030 and projected changes in the MINK economy, the worst-case loss of feedgrains to the meat production sector in the year 2030 could result in a 10% loss in regional production. If CO_2 fertilization and farmer adjustments should lead to yield increases, however, the economic production of the region as a whole would benefit.

Summary

The Resources Analysis Program is involved in analysis of the potential impacts of climate change on natural and human resources at the regional level. The current work represents several advances over previous analyses: 1) the study deals with the region as a whole rather than isolated resources or sectors; 2) CO_2 fertilization and climate change are treated realistically in submodels of plant physiology; 3) technological change and the other effects of time are incorporated in the analysis; 4) regional context is established, with external influences such as world crop prices treated explicitly; 5) the analysis also explicitly accounts for uncertainty.

Acknowledgments

This article is submitted on behalf of a study team with members from PNL, Resources for the Future (RFF), and Oak Ridge National Laboratory (ORNL). The senior members of the study team are Jae Edmonds and Al Liebetrau of PNL; Norm Rosenberg, Bill Easterling, Mary McKenney, Pierre Crosson, Michael Bowes, Ken Frederick, Joel Darmstadter, and Roger Sedjo of RFF; Bob Cushman and Carolyn Hunsaker of ORNL; and Gary Yohe and Tom Malone from Sigma Xi.

References

Easterling, W. E., III, M. L. Parry, and P. R. Crosson. 1989. "Adapting Future Agriculture to Changes in Climate." In *Greenhouse Warming: Abatement and Adaptation*, eds. N. J. Rosenberg, W. Easterling, III, P. R. Crosson, and J. Darmstadter. Resources for the Future, Washington, D.C.

Edmonds, J. A., et al. 1989. "Criteria for Selecting a CO_2/Climate Change Region of Study." Paper 89-148.7. Presented at the 82nd Annual Meeting and Exhibition, Air and Waste Management Association, Anaheim, California, June 28, 1989.

Martin, P., N. J. Rosenberg, and M. S. McKenney. 1989. "Sensitivity of Evapotranspiration in a Wheat Field, a Forest and a Grassland to Changes in Climate and Direct Effects of Carbon Dioxide." *Climatic Change* 14:117-151.

Scott, M. J., et al. 1990. "Consequences of Climatic Change for the Human Environment." *Climate Research* 1(1):63-79.

Solomon, A. M., et al. 1984. *Response of Unmanaged Forests to CO_2 Induced Climate Change: Available Information, Initial Tests, and Data Requirements*. U.S. DOE TR009, NBB-0053, U.S. Department of Energy, Washington, D.C.

Solomon, A. M., and D. C. West. 1987. "Simulating Forest Ecosystem Responses to Expected Climate Change in Eastern North America: Applications to Decision Making in the Forest Industry. In *The Greenhouse Effect, Climate Change, and U.S. Forests*, ed. W. E. Shands. Conservation Foundation, Washington, D.C.

Sonka, S. T., and P. Lamb. 1987. "On Climate Change and Economic Analysis." *Climatic Change* 11:291-312.

Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. "A Modeling Approach to Determining the Relationship Between Erosion and Soil Productivity." *Transactions of the American Society of Agricultural Engineers* 27:129-144.

Publications and Presentations

PUBLICATIONS

Bader, D. C., and T. W. Horst. 1990. "Model Evaluation of the Assumptions Used in Valley Energy Budgets." In *Proceedings of the Fifth Conference on Mountain Meteorology*, pp. 277-280. American Meteorological Society, Boston, Massachusetts.

Bader, D. C., and T. B. McKee. 1991. "Mesoscale Boundary Layer Evolution Over Complex Terrain. Part II. Factors Controlling Nocturnal Boundary Layer Structure." Submitted to *Monthly Weather Review*.

Barns, D. 1990. *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions*. Technical Report TR047, U.S. Department of Energy, Washington, D.C.

Berkowitz, C. M. 1991. "The Response of Sulfate Linearity and Precipitation Chemistry to Gas Phase Profiles." *Atmospheric Environment* (in press).

Chapman, E. G., C. Bapinaga, R. Smith, H. Udseth. 1990. "Confirmation and Quantitation of Hydroxymethane Sulfonate in Precipitation by Electrospray Ionization - Tandem Mass Spectrometry." Submitted to *Atmospheric Environment*.

Doran, J. C. 1990. "The Effect of Ambient Winds on Valley Drainage Winds." In *Proceedings of the Fifth Conference on Mountain Meteorology*, pp. 283-288. American Meteorological Society, Boston, Massachusetts.

Doran, J. C., T. W. Horst, and C. D. Whiteman. 1990. "The Development and Structure of Nocturnal Slope Winds in a Simple Valley." *Boundary-Layer Meteorology* 52:41-68.

Elderkin, C. E., and G. N. Kelly, eds. 1990. *Proceedings of the CEC/USDOE Workshop on Uncertainty Analysis*. CONF-8911195, National Technical Information Service, Springfield, Virginia.

Hales, J. M. 1990. "A Modeling Investigation of Nonlinearities in the Wet Removal of SO_2 Emitted by Urban Sources." In *Atmospheric Chemistry: Models and Predictions for Climate and for Air Quality*. Lewis Publishers, Chelsea, Michigan.

Hales, J. M., and D. S. Renne. 1990. "Atmospheric Source-Receptor Relationships: Concepts and Terminology." Submitted to *Tellus*.

Liebetrau, A. M., and M. J. Scott. 1990. "Hierarchical Analysis Strategies for Modeling the Uncertainty Impacts of Climate Change." Submitted to *Journal of Policy Modeling*.

MacCracken, M., et al. (contributing authors J. A. Edmonds and M. J. Scott). 1990. Energy and Climate Change. UCRL-102476, Lewis Publishers, Chelsea, Michigan.

Patrinos, A. A., R. E. Ellingson, G. M. Stokes, and D. Sowle. 1990. "The Department of Energy Initiative on Atmospheric Radiation Measurements: A Study of Radiation Forcing and Feedbacks." In *Proceedings of a Conference on Atmospheric Radiation*, July 23-27, 1990, San Francisco, California. American Meteorological Society, Boston, Massachusetts.

Scott, M. J., and C. A. Counts, eds. 1990. "Global Warming: A Northwest Perspective." In *Proceedings of a Symposium for the Northwest Power Planning Council*. PNL-SA-17905, Pacific Northwest Laboratory, Richland, Washington.

Scott, M. J., J. A. Edmonds, M. Kellogg, and R. Schultz. 1990. "Global Energy and the Greenhouse Issue." *Energy and Environment* 1(1):74-91.

Scott, M. J., J. A. Edmonds, A. M. Liebetrau, and J. M. Hales. 1990. "Consequences of Climatic Change for the Human Environment." Submitted to *Climate Research*.

Scott, M. J., N. J. Rosenberg, J. A. Edmonds, R. M. Cushman, D. F. Darwin, G. W. Yohe, A. M. Liebetrau, C. T. Hunsaker, D. A. Bruns, D. L. DeAngelis, and J. M. Hales. 1990. "Consequences of Climatic Change for the Human Environment." *Climate Res.* 1(1):63-79.

Scott, M. J., N. J. Rosenberg, J. A. Edmonds, R. G. Cushman, G. W. Yohe, A. M. Liebetrau, C. T. Hunsaker, D. L. DeAngelis, and J. M. Hales. 1990. "Consequences of Climatic Change for the Human Environment." In *Energy and Climate Change: Report of the DOE Multi-Laboratory Climate Change Committee*, pp. 95-120. Lewis, Chelsea, Michigan.

Sisterson, D. L., J. D. Shannon, P. H. Daum, P. J. Klotz, D. J. Luecken, and D. J. Hall. 1989. "The Snowfall Chemistry Collector Intercomparison Test (SCCIT)." *Water, Air, and Soil Pollution* 48:477-488.

Skyllingstad, E. D. 1990. "Critical Layer Effects on Atmospheric Solitary and Cnoidal Waves." Submitted to the *Journal of Atmospheric Sciences*.

Skyllingstad, E. D., and J. C. Doran. 1990. "Terrain-Induced Mesoscale Circulations in the Columbia Basin." In *Proceedings of the Fifth Conference on Mountain Meteorology*, pp. 107-113. American Meteorological Society, Boston, Massachusetts.

Slinn, W.G.N. 1990. "Hints of Another Gremlin in the Greenhouse: Anthropogenic Sulfur." *Atmospheric Environment* (in press).

Slinn, W.G.N., and A.A.N. Patrinos. 1990. "Practical Problems in Improving Climate Models." Submitted to *Earth Quest*.

Tomich, S. D., and M. T. Dana. 1989. "Computer Controlled Automated Rain Sampler (CCARS) for Rainfall Measurement and Sequential Sampling." *J. of Oceanic and Atmospheric Technology* 7:541-549.

Whiteman, C. D. 1990. "Energetics of Valley and Basin Atmospheres During the Evening Transition and Nighttime Periods." In *Proceedings of the Fifth Conference on Mountain Meteorology*, pp. 266-268. American Meteorological Society, Boston, Massachusetts.

Whiteman, C. D. 1990. "Observations of Thermally-Developed Wind Systems in Mountainous Terrain." Chapter 2 of *Atmospheric Processes Over Complex Terrain*, W. Blumen, ed., pp. 5-42. Meteorological Monograph Series 45, American Meteorology Society, Boston, Massachusetts.

PRESENTATIONS

Asher, W. E., N. S. Bloom, E. A. Crecelius, and E. C. Monahan. 1990. "Correlation of Fractional Foam Cover with Gas/Liquid Mass Transport Rates." Presented at the AGU-ASLO 1990 Ocean Sciences Meeting, February 12-16, 1990, New Orleans, Louisiana.

Asher, W. E., and E. C. Monahan. 1990. "Correlation of Fractional Foam Coverage with Gas Transport Rates." Presented at the 2nd International Symposium on Gas Transfer at Water Surfaces, September 11-14, 1990, Minneapolis, Minnesota.

Berkowitz, C. M. 1990. "FBS Application: the RADM Scavenging Model Evaluation." Presented at the NAS Review of DOE Atmospheric Chemistry Program, September 25-26, 1990, Washington, D.C.

Crosson, P. R., and N. J. Rosenberg. 1990. "Regional Impacts of and Responses to Climate Change." Paper presented at the 1990 Annual Meeting of the American Association for the Advancement of Science, February 15-20, 1990, New Orleans, Louisiana.

Dana, M. T. 1990. "DOE Frontal Boundary Study (FBS): Design Overview and Results." Presented at the NAS Review of DOE Atmospheric Chemistry Program, September 25-26, 1990, Washington, D.C.

Dixon, R. W., et al. 1989. "Cloudwater Composition From Mohnen Type Slotted Rod and Counter-Flow Virtual Impactor Probes During PSI-1." Presented at the American Geophysical Union Fall Meeting, December 4-8, 1989, San Francisco, California.

Edmonds, J. A. 1990. "Uncertainties in Energy Scenarios and Their Consequences for CO_2 Emissions." Presented to the International Union of Pure and Applied Chemistry, Workshop on the Assessment of Uncertainties in the Projected Concentrations of CO_2, July 4-6, 1990, Petten, Netherlands.

Elderkin, C. E., Gudiksen, P. W., W. E. Clements, R. P. Hosker, Jr., C. D. Whiteman, W. D. Neff, R. L. Coulter, and G. E. Start. 1989. "Field Studies for Determining the Characteristics and Dynamics of Local Circulations." Presented at the U.S.-India Workshop on Environmental Risk Analysis, December 12-16, 1989, New Delhi, India.

Ghan, S. J. 1990. "Cloud Parameterizations in Global and Regional Models." Presented at the NAS Review of DOE Atmospheric Chemistry Program, September 25-26, 1990, Washington, D.C.

Hales, J. M. 1990. "Overview of Global and Mesoscale Modeling." Presented at the NAS Review of DOE Atmospheric Chemistry Program, September 25-27, 1990, Washington, D.C.

Lee, R. N., and K. M. Busness. 1989. "The Concentration and Vertical Distribution of Peroxides Over the Pacific Ocean During the Pacific Stratus Investigation (PSI)." Presented at the American Geophysical Union 1989 Fall meeting, December 4-8, 1989, San Francisco, California.

Liebetrau, A. M., M. J. Scott, W. Easterling, and M. McKenney. 1990. "Sensitivity and Uncertainty Analysis of Crop Yield Estimates Computed Using the EPIC Model." Presented at the Third Interdisciplinary Conference on Natural Resource Modeling, Cornell University, October 11-13, 1990, Ithaca, New York.

Michael, P., et al. 1989. "Pollutant Distributions in Extratropical Cyclones." Presented at the American Geophysical Union Fall Meeting, December 4-8, 1989, San Francisco, California.

Rosenberg, N. J. 1990. "A Methodology for Identifying Regional Influences of an Responses to Increasing Atmospheric CO_2 and Climate Change." Paper presented at the Symposium on Biometeorology and Global Change, February 4-9, 1990, Anaheim, California.

Scott, M. J. 1989. "Global Environmental Change and Socioeconomic Impacts: Estimating Costs to Society." Presented at the Hanford Technical Exchange, October 11, 1989, Richland, Washington.

Scott, M. J. 1989. "Pacific Northwest Global Climate Effects Case Study: Overview of Resource Implications and Impacts." Presented at Participants Meeting on Pacific Northwest Global Climate Effects Case Study, October 13, 1989, Portland, Oregon.

Scott, M. J. 1990. "Global Warming Impacts: Integrating Research and Policy." Presented at the Second Annual Research Briefing on Texas and Global Warming, Center for Growth Studies, University of Texas, May 4, 1990, Austin, Texas.

Shankle, S. A., M. J. Scott, J. C. Chatters, and D. A. Neitzel. 1990. "Global Climate Change and Effects on Pacific Northwest Salmonids: An Exploratory Case." Paper presented at the 37th Annual Pacific Northwest Regional Meeting of American Geophysical Union, September 13-14, 1990, Seattle, Washington.

Slinn, W.G.N. 1989. "Constraints from Data on Suggested Influences of Natural and Anthropogenic Sulfur on Climate Change." Presented at the Eighth Annual Meeting of the American Association for Aerosol Research, Symposium on Global Climatic Effects of Aerosols, October 10-13, 1989, Reno, Nevada.

Yohe, G. W. 1990. "Toward a General Criterion for Selecting Interesting Scenarios with Which to Analyze Adaptive and Averting Response to Potential Climate Change." Paper presented at the International Workshop on the Natural Resources and Economic Implications of Global Climate Change, November 5-9, 1990, Interlaken, Switzerland.

Author Index

AUTHOR INDEX

Allwine, K. J.; 3
Asher, W. E.; 28

Bader, D. C.; 8
Berkowitz, C. M.; 9
Busness, K. M.; 9, 16

Dana, M. Terry; 9
Davis, W. E.; 9
Denbo, D. W.; 28
Doran, J. C.; 3
Downing, J. P.; 28

Easter, R. C.; 9
Edmonds, J. A.; 34

Hannigan, R. V.; 9
Hubbe, J. M.; 3

Lee, R. N.; 9
Luecken, D. J.; 9

Richmond, M. C.; 28

Scott, M. J.; 35
Sharp, D. S.; 9
Skyllingstad, E. D.; 28
Stokes, G. M.; 23

Thorp, J. M.; 9
Tomich, S. D.; 9

Whiteman, C. D.; 5

Distribution

DISTRIBUTION

No. of
Copies

OFFSITE

12 DOE/Office of Scientific
and Technical Information

R. E. Alexander
ORPBR, NL
U.S. Nuclear Regulatory
Commission
Washington, DC 20545

D. R. Anderson
ENVIROTEST
1206A N. 185th
Seattle, WA 98133-4020

Assistant Secretary
Environment, Safety &
Health
EH-1, FORS
Department of Energy
Washington, DC 20585

J. A. Auxier
IT Corporation
312 Director's Dr.
Knoxville, TN 37701

F. Badgley
13749 41st Street, N.E.
Seattle, WA 98125

R. E. Baker
8904 Roundleaf Way
Gaithersburg, MD
20879-1630

D. Baldocchi
Atmospheric Turbulence
and Diffusion Laboratory
National Oceanic
and Atmospheric
Administration
P.O. Box 2456
Oak Ridge, TN 37830

No. of
Copies

R. W. Barber
EH-131, GTN
U.S. Department of Energy
Washington, DC 20545

A. D. Barker
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

J. R. Barker
Office of Environmental
Audit and Compliance
U.S. Department of Energy
Washington, DC 20545

H. M. Barnes
AREAL (MD-39)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

N. F. Barr
ER-72, GTN
U.S. Department of Energy
Washington, DC 20545

S. Barr
Environmental Studies
Group
MS-F665
Los Alamos National
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

J. F. Boatman
NOAA/R/E/AR4
325 Broadway
Boulder, CO 80303

L. C. Brazley, Jr.
NE-22, GTN
U.S. Department of Energy
Washington, DC 20545

No. of
Copies

J. C. Brown
Environmental Studies
Group
MS-A114
Los Alamos National
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

P. Buhl
FE-232, GTN
U.S. Department of Energy
Washington, DC 20545

G. Burley
Office of Radiation
Programs (ANR-458)
U.S. Environmental
Protection Agency
Washington, DC 20460

W. W. Burr
Medical & Health Sciences
Division
Oak Ridge Associated
Universities
P.O. Box 117
Oak Ridge, TN 37830

L. K. Bustad
College of Veterinary
Medicine
Washington State
University
Pullman, WA 99164-7010

R. J. Catlin
U.T. Health Science Center-
Houston
13307 Queensbury Lane
Houston, TX 77079

No. of
Copies

J. S. Chang
Atmospheric Sciences
Research Center
State University of New
York at Albany
100 Fuller Road
Albany, NY 80307

R. J. Charlson
Department of
Atmospheric Sciences,
AK-40
University of Washington
Seattle, WA 98195

J.K.S. Ching
AREAL (MD-80)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

Council on Environmental
Quality
722 Jackson Place, NW
Washington, DC 20503

T. V. Crawford
Westinghouse
Atomic Energy Division
Savannah River Laboratory
Aiken, SC 29808

J. B. Cunning
NOAA/ERL
325 Broadway
Boulder, CO 80303

P. H. Daum
Brookhaven National
Laboratory
Upton, Long Island,
NY 11973

J. Decker
ER-1, FORS
U.S. Department of Energy
Washington, DC 20545

No. of
Copies

K. Demerjian
Atmospheric Sciences
Research Center
State University of New
York at Albany
100 Fuller Road
Albany, NY 80307

R. L. Dennis
AREAL (MD-80)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

G. DePlanque, Director
Environmental Measure-
ments Laboratory
U.S. Department of Energy
375 Hudson Street
New York, NY 10014

M. H. Dickerson
Lawrence Livermore
National Laboratory
L-262
P.O. Box 808
Livermore, CA 94550

R. R. Dickerson
Department of Meteorology
University of Maryland
College Park, MD 20742

H. Drucker
Argonne National
Laboratory
9700 South Cass Avenue
Argonne, IL 60439

A. P. Duhamel
ER-74, GTN
U.S. Department of Energy
Washington, DC 20545

No. of
Copies

C. W. Edington, Director
Board on Radiation Effects
Research
National Research Council
2101 Constitution Avenue,
NW
Washington, DC 20418

R. J. Engelmann
11701 Karen
Potomac, MD 20854

B. H. Fimiani
Pacific Northwest Laboratory
Washington Operations
370 L'Enfant Promenade,
Suite 900
901 D Street, SW
Washington, DC 20024

G. J. Foley
AREAL (MD-75)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

D. J. Galas
ER-70, GTN
U.S. Department of Energy
Washington, DC 20585

T. F. Gesell
Idaho Operations Office
U.S. Department of Energy
785 DOE Place
Idaho Falls, ID 83402-4149

R. D. Gilmore
Environmental Health
Sciences, Inc.
Nine Lake Bellevue
Building, Suite 104
Bellevue, WA 98005

No. of
Copies

G. H. Groenewold
Energy and Mineral
Research Center
University of North Dakota
Box 8213, University
Station
Grand Forks, ND 58202

T. Gross
ER-76, GTN
U.S. Department of Energy
Washington, DC 20545

J. W. Healy
51 Grand Canyon Drive
White Rock, NM 87544

B. B. Hicks
NOAA-ARL
1325 East-West Highway,
Rm. 9348
Silver Spring, MD 20910

T. W. Horst
Surface and Sounding
Systems Facility
Atmospheric Technology
Division
National Center for
Atmospheric Research
P.O. Box 3000
Boulder, CO 80307-3000

F. Hutchinson
Department of Molecular
Biophysics and
Biochemistry
Yale University
260 Whitney Ave.
P.O. Box 6666
New Haven, CT 06511

P. Irving
National Acid Precipitation
Assessment Program
722 Jackson St.
Washington, DC 20006

No. of
Copies

H. Ishikawa
Nuclear Safety Research
Association
P.O. Box 1307
Falls Church, VA 22041

A. W. Johnson
Vice President for
Academic Affairs
San Diego State University
San Diego, CA 92128

L. J. Johnson
Idaho National Engineering
Lab
IRC MS 2203
P.O. Box 1625
Idaho Falls, ID 83415

G. Y. Jordy
ER-30, GTN
U.S. Department of Energy
Washington, DC 20545

F. Koomonoff
ER-12, GTN
U.S. Department of Energy
Washington, DC 20545

R. Kornasiewicz
Mail Stop 1130-55, ONRR
U.S. Nuclear Regulatory
Commission
Washington, DC 20555

D. Lal
Geological Research
Division A-020
Scripps Institute of
Oceanography
La Jolla, CA 92093

T. V. Larsen
Department of Civil
Engineering
University of Washington
Seattle, WA 98195

No. of
Copies

L. Levin
Electric Power Research
Institute
3412 Hillview Ave.
P.O. Box 10412
Palo Alto, CA 94303

Librarian
Brookhaven National
Laboratory
Research Library,
Reference
Upton, Long Island,
NY 11973

Librarian
Colorado State University
Documents Department—
The Libraries
Ft. Collins, CO 80521

Librarian
Electric Power Research
Institute
3412 Hillview Ave.
P.O. Box 10412
Palo Alto, CA 94303

Librarian
Atmospheric Sciences
Library, AK-50
University of Washington
Seattle, WA 98195

Librarian
Los Alamos National
Laboratory
MS P364
P.O. Box 1663
Los Alamos, NM 87545

Librarian
National Oceanic and
Atmospheric
Administration
Atmospheric Turbulence
and Diffusion Laboratory
P.O. Box 2456
Oak Ridge, TN 37831

No. of Copies

Librarian
Washington State University
Pullman, WA 99164-6510

Library
Serials Department (#80-170187)
University of Chicago
1100 East 57th Street
Chicago, IL 60637

I. R. Linger
ER-63, GTN
U.S. Department of Energy
Washington, DC 20545

D. L. Lundgren
Lovelace - ITRI
P.O. Box 5890
Albuquerque, NM 87185

O. R. Lunt
Laboratory of Nuclear Medicine and Radiation Biology
University of California
900 Veteran Avenue
West Los Angeles, CA 90024

J. N. Maddox
ER-73, GTN
U.S. Department of Energy
Washington, DC 20545

W. J. Madia
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

J. R. Maher
ER-65, GTN
U.S. Department of Energy
Washington, DC 20545

No. of Copies

B. Manowitz
Energy and Environment Division
Brookhaven National Laboratory
Upton, Long Island, NY 11973

S. Marks
8024 47th Place West
Mukilteo, WA 98275

D. D. Mayhew
ER-63, GTN
U.S. Department of Energy
Washington, DC 20545

H. M. McCammon
ER-75, GTN
U.S. Department of Energy
Washington, DC 20545

C. B. Meinhold
Radiological Sciences Division
Bldg. 703M
Brookhaven National Laboratory
Upton, Long Island, NY 11973

M. L. Mendelsohn
Biomedical and Environmental Research Program
Lawrence Livermore National Laboratory, L-452
University of California
P.O. Box 5507
Livermore, CA 94550

P. Michael
Brookhaven National Laboratory
Upton, Long Island, NY 11973

No. of Copies

C. Miller
P.O. Box 180
Watermill, NY 11976

M. L. Minthorn, Jr.
ER-72, GTN
U.S. Department of Energy
Washington, DC 20545

V. Mohnen
State University of New York at Albany
100 Fuller Road
Albany, NY 80307

B. Morgan
Environmental Division
DOE - Savannah River Operations Office
P.O. Box A
Aiken, SC 29801

H. Moses
ER-76, GTN
U.S. Department of Energy
Washington, DC 20545

P. K. Mueller
Environmental Science Department
Electric Power Research Institute
3412 Hillview Ave.
P.O. Box 10412
Palo Alto, CA 94304

R. Nathan
Battelle Project Management Division
505 King Avenue
Columbus, OH 43201

W. Neff
Wave Propogation Lab, NOAA
325 Broadway
Boulder, CO 80303

No. of
Copies

L. Newman
Brookhaven National
Laboratory
Upton, Long Island,
NY 11973

W. R. Ney
National Council on
Radiation Protection
and Measurements
Suite 1016
7910 Woodmont Avenue
Bethesda, MD 20814

Nuclear Regulatory
Commission
Advisory Committee on
Reactor Safeguards
Washington, DC 20555

M. J. O'Brien
Radiation Safety Office,
GS-05
University of Washington
Seattle, WA 98105

A. A. Patrinos
ER-76, GTN
U.S. Department of Energy
Washington, DC 20545

R. Pawr
AREAL (MD-44)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

A. A. Pitrolo
Morgantown Energy
Research Center
U.S. Department of Energy
P.O. Box 880
Morgantown, WV 26505

D. P. Rall
NIEHS
P.O. Box 12233
Research Triangle Park,
NC 27709

No. of
Copies

M. R. Riches
ER-76, GTN
U.S. Department of Energy
Washington, DC 20545

C. R. Richmond
Oak Ridge National
Laboratory
4500N, MS-62523
P.O. Box 2008
Oak Ridge,
TN 37831-6253

S. L. Rose
ER-73, GTN
U.S. Department of Energy
Washington, DC 20545

R. D. Rosen
Environmental Measure-
ments Laboratory
U.S. Department of Energy
376 Hudson Street
New York, NY 10014

J. M. Rusin
404 W. Halladay
Seattle, WA 98119

P. Samson
Atmospheric and Oceanic
Sciences
University of Michigan
Ann Arbor, MI 48109

R. A. Scarano
Mill Licensing Section
U.S. Nuclear Regulatory
Commission
Washington, DC 20545

F. A. Schiermeier
Atmospheric Sciences
Modeling Division
(MD-80)
U.S. Environmental
Protection Agency
Research Triangle Park,
NC 27711

No. of
Copies

M. Schulman
ER-70, GTN
U.S. Department of Energy
Washington, DC 20545

R. B. Setlow
Brookhaven National
Laboratory
Upton, Island,
NY 11973

R. Shikiar
Battelle - Seattle
4000 NE 41st Street
Seattle, WA 98105

P. Silverman
Lawrence Berkeley
Laboratory
Bldg. 50A/5104
Berkeley, CA 94720

W. K. Sinclair
National Council on
Radiation Protection
and Measurements
Suite 1016
7910 Woodmont Avenue
Bethesda, MD 20814

C. Spicer
Battelle Columbus
Division
505 King Avenue
Columbus, OH 43201

J. N. Stannard
17441 Plaza Animado
#132
San Diego, CA 92128

R. J. Stern
EH-10, FORS
U.S. Department of Energy
Washington, DC 20585

No. of
Copies

J. F. Stevens
Dayton Area Office
DOE - Albuquerque
Operations Office
P.O. Box 66
Miamisburg, OH 45342

E. T. Still
Kerr-McGee Corporation
P.O. Box 25861
Oklahoma City, OK 73125

P. Stone
ER-6, FORS
U.S. Department of Energy
Washington, DC 20585

G. M. Sverdrup
Battelle Columbus
Division
505 King Avenue
Columbus, OH 43201

J. Swinebroad
EH-12, GTN
U.S. Department of Energy
Washington, DC 20545

Technical Information
Service
Westinghouse
Savannah River Laboratory
Room 773A
Aiken, SC 29801

U.S. Department of Energy
Environment, Safety and
Health Division
P.O. Box 5400
Albuquerque, NM 87115

E. J. Vallario
15228 Red Clover Drive
Rockville, MD 20853

B. Vallet
NORCUS
390 Hanford St.
Richland, WA 99352

No. of
Copies

C. R. Vest
Pacific Northwest
Laboratory
Washington Operations
370 L'Enfant Promenade,
Suite 900
901 D Street, SW
Washington, DC 20024

G. J. Vodapivc
DOE - Schenectady Naval
Reactors Office
P.O. Box 1069
Schenectady, NY 12301

B. W. Wachholz
Radiation Effects Branch
National Cancer Institute
EPN, Room 530
8000 Rockville Pike
Bethesda, MD 20892

R. A. Walters
Los Alamos National
Laboratory
MS-A114
P.O. Box 1663
Los Alamos, NM 87545

C. G. Welty, Jr.
EH-123, GTN
U.S. Department of Energy
Washington, DC 20545

I. Wender
Department of Chemical
Engineering
1249 Benedum Hall
University of Pittsburgh
Pittsburgh, PA 15261

M. L. Wesely
Argonne National
Laboratory
Building 203, ER
Argonne, IL 60439

No. of
Copies

W. W. Weyzen
Electric Power Research
Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 92665

R. W. Wood
ER-74, GTN
U.S. Department of Energy
Washington, DC 20545

Zhu Zhixian
Laboratory for Energy-
Related Health Research
University of California
Davis, CA 95616

FOREIGN

E. L. Alpen
University of California
Study Center
21 Stratton Ground
London SW1 P2HY
ENGLAND

W. A. Asman
National Environmental
Institute
P.O. Box 1
NL-3720 BA Bilthoven
THE NETHERLANDS

D. C. Aumann
Institut für Physikalische
Chemie
Der Universität Bonn
Abt. Nuklearchemie
Wegelerstraße 12
5300 Bonn 1
GERMANY

J. K. Basson
Raad Op Atomic
Atoomkrag Energy Board
Privaatsk X 256
Pretoria 0001
REPUBLIC OF SOUTH
AFRICA

No. of
Copies

A. M. Beau, Librarian
Commissariat à l'Energie Atomique
Départment de Protection Sanitaire
BP No. 6
F-92260 Fontenay-aux-Roses
FRANCE

G. Bengtsson
Statens Stralskyddsinstitut
Box 60204
S-104 01 Stockholm
SWEDEN

D. J. Beninson
Gerencia de Protection Radiologica y Seguridad
Comision Nacional de Energia Atomica
Avenida del Libertador 8250
1429 Buenos Aires
ARGENTINA

R. Berkowicz
Air Pollution Laboratory
National Agency for Environmental Protection
Risø National Laboratory
DK-4000 Roskilde
DENMARK

Cao Shu-yuan, Deputy Head
Laboratory of Radiation Medicine
North China Institute of Radiation Protection
Tal-yuan, Shan-xi
THE PEOPLE'S REPUBLIC OF CHINA

M. Carpentier
Commission of the E.C.
200 Rue de la Loi
J-70 6/16
B-1049 Brussels
BELGIUM

No. of
Copies

CEC
DG XII Library
SDM8 R1
200 Rue de la Loi
B-1049 Brussels
BELGIUM

Chen Xing-an, M.D.
Laboratory of Industrial Hygiene
Ministry of Public Health
2 Xinkang Street
Deshengmanwai, Beijing
THE PEOPLE'S REPUBLIC OF CHINA

G. H. Clark
Australian Nuclear Science and Technology Organization
Environmental Science Division
Private Mail Bag 1
Menai NSW 2234
AUSTRALIA

R. Clarke
National Radiological Protection Board
Harwell, Didcot
Oxon OX11 ORQ
ENGLAND

P. Crutzen
Atmospheric Chemistry
Max-Planck-Institut für Chemie
Postfach 3060
D-6500 Mainz
GERMANY

F.A.A.M. de Leeuw
Laboratory for Air Research
RIVM
P.O. Box 1
NL-3720 BA Bilthoven
THE NETHERLANDS

No. of
Copies

Deng Zhicheng
North China Institute of Radiation Protection
Tai-yuan, Shan-xi
THE PEOPLE'S REPUBLIC OF CHINA

Director
Commissariat à l'Energie Atomique
Centre d'Etudes Nucléaires
Fontenay-aux-Roses (Seine)
FRANCE

Director
Commonwealth Scientific and Industrial Research Organization
Aspendal, Victoria
AUSTRALIA

Director
Laboratorio di Radiobiologia Animale
Centro di Studi Nucleari Della Casaccia
Comitate Nazionale per l'Energia Nucleare
Casella Postale 2400
00100 Roma
ITALY

D. Djuric
Institute of Occupational and Radiological Health
11000 Beograd
Deligradoka 29
YUGOSLAVIA

H. Dovland
Director
Norwegian Institute for Air Research
Elvegaten 52
N-2001 Lilleström
NORWAY

No. of
Copies

L. Feinendegen, Director
Institut für Medezin
Kernsforschungsanlage
Jülich
Postfach 1913
D-5170 Jülich
GERMANY

R. M. Fry
Office of the Supervising
Scientist for the
Alligator Rivers Region
P.O. Box 387
Bondi Junction NSW 2022
AUSTRALIA

G. B. Gerber
Radiobiology Department
Commission of European
Communities
200 Rue de la Loi
B-1049 Brussels
BELGIUM

A. R. Gopal-Ayengar
73-Mysore Colony
Mahul Road, Chembur
Bombay-400 074
INDIA

P. Grennfelt
Swedish Environmental
Research Institute
P.O. Box 47086
S-402 58 Göteborg
SWEDEN

S. E. Gryning
Physics and Meteorology
Risø National Laboratory
DK-4000 Roskilde
DENMARK

G. F. Gualdrini
ENEA
3 v. le Ercolani
I-40138 Bologna
ITALY

No. of
Copies

J. L. Head
Department of Nuclear
Science & Technology
Royal Naval College,
Greenwich
London SE10 9NN
ENGLAND

O. Hov
Norwegian Institute for
Air Research
Allegaten 70
N-5007 Lillestrõm
NORWAY

P. Hummelshoej
Physics and Meteorology
Risø National Laboratory
DK-4000 Roskilde
DENMARK

K. E. Lennart Johansson
Radiofysiska Inst.
Regionsjukhuset
S-901 82 Umeå
SWEDEN

G. N. Kelly
Commission of the
European Communities
Directorate-General
Joint Research Centre
200 Rue de la Loi
B-1049 Brussels
BELGIUM

J. Kjems
Risø National Laboratory
DK-4000 Roskilde
DENMARK

H. J. Klimisch
BASF Aktiengesellschaft
Abteilung Toxikologie
Z470
D-6700 Ludwigshafen
GERMANY

No. of
Copies

L. Kristensen
Physics and Meteorology
Risø National Laboratory
DK-4000 Roskilde
DENMARK

T. Kumatori
The Radiation Effects
Association
9-16, Kajicho-1,
Chiyodaku, Tokyo 101
JAPAN

A. Lacser
Israel Institute of
Biological Research
Department of Mathematics
P.O. Box 19
7004 50
Ness-Ziona
ISRAEL

S. E. Larsen
Physics and Meteorology
Risø National Laboratory
DK-4000 Roskilde
DENMARK

H. P. Leenmouts
National Institute of
Public Health and
Environmental Hygiene
P.O. Box 1
NL-3720 BA, Bilthoven
THE NETHERLANDS

Li De-ping
Professor and Director
of North China Institute
of Radiation Protection,
NMI
Tai-yuan, Shan-xi
THE PEOPLE'S
REPUBLIC OF CHINA

No. of
Copies

Librarian
Centre d'Etudes
Nucléaires de Saclay
P.O. Box 2, Saclay
Fig-sur-Yvette (S&O)
FRANCE

Librarian
Commonwealth Scientific
and Industrial Research
Organization
314 Albert Street
P.O. Box 89
East Melbourne, Victoria
AUSTRALIA

Librarian
Commonwealth Scientific
and Industrial Research
Organization
Div. of Atmospheric
Research
Station Street
Aspendale, Vic. 3195
AUSTRALIA

Librarian
ECN
3 Westerdiunweg
NL-1755 ZG Petten
THE NETHERLANDS

Librarian
ENEA (OECD) Health and
Safety Office
38, Blvd. Suchet
Paris
FRANCE

Librarian
Fraunhofer Institute
for Atmospheric
Environmental Research
Kreuzeckbahnstr. 19
D-8100 Garmisch-
Partenkirchen
GERMANY

No. of
Copies

Librarian
HCS/EHE
World Health Organization
CH-1211 Geneva 27
SWITZERLAND

Librarian
Kernforschungzentrum
Karlsruhe
Institut für
Strahlenbiologie
D-75 Karlsruhe 1
Postfach 3640
GERMANY

Librarian
Max-Planck-Institut für
Biophysics
Forstkasstrasse
D-6000 Frankfurt/Main
GERMANY

Librarian
Ministry of Agriculture,
Fisheries and Food
Fisheries Laboratory
Lowestoft, Suffolk
NR33 OHT
ENGLAND

Librarian
National Institute of
Radiological Sciences
9-1, Anagawa 4-chome
Chiba-shi 260
JAPAN

Library
Risø National Laboratory
DK-4000 Roskilde
DENMARK

Library, Periodicals
Atomic Energy
Commission of
Canada, Ltd.
Pinawa, Manitoba R0E 1L0
CANADA

No. of
Copies

Library
Department of Meteorology
University of Stockholm
Arrhenius Laboratory
S-106 91 Stockholm
SWEDEN

A. M. Marko
Atomic Energy Commis-
sion of Canada, Ltd.
Biology and Health Physics
Division
Chalk River Nuclear
Laboratories
P.O. Box 62
Chalk River, Ontario
K0J 1J0
CANADA

H. Matsudaira,
Director-General
National Institute of
Radiological Sciences
9-1, Anagawa-4-chome
Chiba-shi 260
JAPAN

J. C. Nénot
Département de Protection
Centre d' Etudes
Nucléaires
BP No. 6
F-92260 Fontenay-aux-
Roses
FRANCE

J. P. Oliver
ENEA (OECD) Health and
Safety Office
38, Blvd. Suchet
Paris
FRANCE

No. of
Copies

R. Osborne
Atomic Energy Commission
of Canada, Ltd.
Biology and Health Physics
Division
Chalk River Nuclear
Laboratories
P.O. Box 62
Chalk River, Ontario
K0J 1J0
CANADA

N. Parmentier
Départment de Protection
Centre d'Etudes
Nucléaires
BP No. 6
F-92260 Fontenay-aux-
Roses
FRANCE

L. Prahm
Danish Meteorological
Institute
Lyngbyvej 100
DK-2100 Copenhagen
East
DENMARK

V. Prodi
Department of Physics
University of Bologna
Via Imerio 46
I-40126 Bologna
ITALY

P. J. A. Rombout
Inhalation of Toxicology
Department
National Institute of
Public Health and
Environmental Hygiene
P.O. Box 1
NL-3720 BA, Bilthoven
THE NETHERLANDS

No. of
Copies

M. Roy
Institut de Protection et
de Sureté Nucléaire
Department de Protection
Sanitaire
Service d'Etudes
Apliquées de Protection
Sanitaire
BP No. 6
F-92260 Fontenay-aux-
Roses
FRANCE

M. Rzekiecki
Commissariat à l'Energie
Atomique
Centre d'Etudes
Nucléaires de Cadarache
BP No. 13-St. Paul
Les Durance
FRANCE

G. Schnatz
Battelle-Europe eV
Am Römerhof 35
P.O. Box 900160
D-6000 Frankfurt a.M.
GERMANY

R. Skogstrom
Meteorological Institute
University of Stockholm
Arrhenius Laboratory
S-106 91 Stockholm
SWEDEN

J. Slanina
ECN
3 Westerduinweg
NL-1755 ZG Petten
THE NETHERLANDS

H. Smith
Biology Department
National Radiological
Protection Board
Chilton, Didcot
Oxon OX11 ORQ
ENGLAND

No. of
Copies

J. W. Stather
National Radiological
Protection Board
Building 383
Harwell, Didcot
Oxon OX11 ORQ
ENGLAND

M. J. Suess
Regional Officer for
Environmental Hazards
World Health Organization
8, Scherfigsvej
DK-2100 Copenhagen
DENMARK

Sun Shi-quan, Head
Radiation-Medicine
Department
North China Institute
of Radiation Protection
Tai-yuan, Shan-xi
THE PEOPLE'S
REPUBLIC OF CHINA

J. W. Thiessen
Radiation Effects Research
Foundation
5-2 Hijiyama Park
Minami - Ward
Hiroshima 732
JAPAN

M. Thorne
International Commission
on Radiological
Protection
Clifton Avenue
Sutton, Surrey
ENGLAND

United Nations Scientific
Committee on the Effects
of Atomic Radiation
Vienna International
Center
P.O. Box 500
A-1400 Vienna
AUSTRIA

No. of
Copies

D. Van As
Atomic Energy Board
Private Bag X256
Pretoria 0001
REPUBLIC OF SOUTH
AFRICA

Vienna International
Centre Library
Gifts and Exchange
P.O. Box 100
A-1400 Vienna
AUSTRIA

Wang Renzhi
Institute of Radiation
Medicine
11# Tai Ping Road
Beijing
THE PEOPLE'S
REPUBLIC OF CHINA

Wang Ruifa
Laboratory of Industrial
Hygiene
Ministry of Public Health
2 Xinkang Street
Deshengmanwai, Beijing
THE PEOPLE'S
REPUBLIC OF CHINA

Wang Yibing
North China Institute
of Radiation Protection
P.O. Box 120
Tai-yuan, Shan-xi
THE PEOPLE'S
REPUBLIC OF CHINA

Wei Luxin
Laboratory of Industrial
Hygiene
Ministry of Public Health
2 Xinkang Street
Deshengmanwai, Beijing
THE PEOPLE'S
REPUBLIC OF CHINA

No. of
Copies

B. C. Winkler
Raad Op Atomic
Atoomkrag Energy Board
Privaatsk X256
Pretoria 0001
REPUBLIC OF SOUTH
AFRICA

Wu De-Chang
Institute of Radiation
Medicine
11# Tai Ping Road
Beijing
THE PEOPLE'S
REPUBLIC OF CHINA

Yao Jiaxiang
2 Xinkang Street
Deshengmenwai
Beijing 100011
THE PEOPLE'S
REPUBLIC OF CHINA

ONSITE

2 DOE Richland Operations Office

E. C. Norman
M. W. Tiernan/
R. D. Freeburg

Washington State University - Tri-Cities

J. Cooper

Hanford Environmental Health Foundation

M. J. Swint

2 Westinghouse Hanford Co.

C. J. Perkins
D. E. Simpson

117 Pacific Northwest Laboratory

O. B. Abbey
R. C. Adams
K. J. Allwine
W. E. Asher
R. W. Baalman
D. C. Bader
J. F. Bagley
W. J. Bair (15)
M. Y. Ballinger
W. R. Barchet
E. M. Baroni
N. S. Bloom
C. J. Brandt
K. M. Busness
E. G. Chapman
T. D. Chikalla
J. F. Clarke
T. T. Claudson
E. A. Crecelius
T. S. Cress
M. T. Dana
W. E. Davis
D. W. Denbo
J. C. Doran
J. P. Downing
R. C. Easter
J. A. Edmonds
C. E. Elderkin (5)
J. W. Falco
S. J. Ghan
C. S. Glantz
W. A. Glass
J. A. Glissmeyer
D. W. Glover
R. H. Gray
R. K. Hadlock
J. M. Hales (3)
R. V. Hannigan
M. S. Hanson
P. C. Hays
C. S. Hillock
D. J. Hoitink
L. A. Holmes
J. R. Houston
J. M. Hubbe
J. R. Johnson
R. A. Keefe

No. of
Copies

E. W. Kleckner
M. L. Knotek
W. W. Laity
N. S. Laulainen
G. L. Laws
R. N. Lee
A. M. Liebetrau
J. C. Liljegren
D. J. Luecken
J. A. Mahaffey
M. E. Mericka
E. L. Owczarski
P. C. Owczarski
J. F. Park
W. T. Pennell

No. of
Copies

J. V. Ramsdell
D. S. Renne
M. C. Richmond
J.T.A. Roberts
D. R. Roth
B. C. Scott
M. J. Scott
D. S. Sharp
W. J. Shaw
B. D. Shipp
R. L. Skaggs
E. D. Skyllingstad
W.G.N. Slinn
G. M. Stokes

No. of
Copies

J. A. Stottlemyre
T. S. Tenforde (2)
J. M. Thorp
B. E. Vaughan
L. L. Wendell (2)
C. D. Whiteman
R. E. Wildung
W. R. Wiley
L. D. Williams
J. D. Zimbrick
Health Physics Library
Life Sciences Library (2)
Publishing Coordination
Technical Report Files (5)