National Center for Atmospheric Research
Annual Scientific Report
Fiscal Year 1990

Submitted to National Science Foundation
by
University Corporation for Atmospheric Research
June 1991

The National Center for Atmospheric Research

This institution is dedicated,
in partnership with the universities,
to excellence in the atmospheric and related sciences,
to the benefit to mankind.

This report is produced in compliance with Article VI, Paragraph 3,
of the current UCAR-NSF contract (ATM-8709659).

Contents

Introduction

The 20th annual Earth Day was celebrated in 1990. As we look back over the last two decades, we see a broadening public awareness of environmental issues, building to a widespread international concern for the changes occurring in the atmosphere and the oceans, and the consequences of human activity on the global environment. As a national center devoted to a serious study of the global earth systems, NCAR is in a key position to serve and foster our understanding of these changes in four major ways.

The first is to provide a collaborative hub for the research community whereby scientists from around the world can join with NCAR to conduct inquiries into the physical and chemical processes of the sun-atmosphere-ocean system, the predictability of weather and climate, human influences on the earth system, and the societal impacts thereof.

Second, NCAR provides the research community with advanced technology to assist these investigations. A CRAY Y-MP8/864 supercomputer, acquired this year, links NCAR to researchers throughout North America and the globe. Aircraft, radars, and a host of other specialized instruments make observations in field projects here and abroad that are central to our search for answers as to how earth systems function.

Third, because of the global nature of our environmental problems and the impact of human activity on the environment, it is essential that the public, here and in other countries, better understand the problems of the environment. A vigorous education program at NCAR seeks to inform students of all ages, the public at large, scientists from throughout the world, and policymakers of the scientific bases for these problems.

Finally, NCAR is well positioned to ensure that the benefits of this publicly funded research are made available to the community through technology transfer. During the 1990s, NCAR will increasingly apply new scientific and technical knowledge to practical problems in order to benefit society both economically and socially.

Highlights of NCAR's achievements in these four area areas during fiscal 1990 are contained in this volume. They reflect the dedication of a staff committed to excellence. Support from the

National Science Foundation and UCAR guidance enable NCAR to continue its leadership and service in the national and international arenas. The NSF support is complemented by support from other agencies—public and private—which serves to strengthen the NCAR program and enhance the NSF-supported research effort. This increasingly diversified support reflects the multidisciplinary and interdisciplinary nature of atmospheric and oceanic research and the fact that the scientific questions with which NCAR is concerned are touching a wider and more complicated world than we knew 20 years ago.

Robert J. Serafin
Director

June 1991

Atmospheric Chemistry Division

The research program of the Atmospheric Chemistry Division (ACD) is directed toward understanding the chemistry of the atmosphere and the global changes caused by the alteration of the composition of the atmosphere, from both natural and human causes. Our research activities emphasize: (1) laboratory and field investigations of reactive gases and aerosols, (2) global distribution of trace species in the troposphere and stratosphere, and (3) organic emission and fate of biogenic trace gases, and the effects of reactive gases on plant processes. To better understand processes controlling the composition of the global atmosphere, computer-based theoretical models are developed to compare with observational data. ACD has made a large commitment to the Global Tropospheric Chemistry Program (GTCP) and the International Global Atmospheric Chemistry Program (IGAC). Preparations for a major one-year field campaign to study the oxidation capacity of the atmosphere and the budget of ozone and other chemical constituents in the free troposphere are now under way.

The scientific program of the division is complemented by collaborations with colleagues at institutions in the United States and other countries. Collaborations in field work, data analysis, and development of equipment and theoretical models are enhanced by the visitor program in the division.

Significant Accomplishments

- Continued development and refinement of chemical, transport, and dynamical models of the lower and middle atmosphere have resulted in significant findings. Among them are (1) excellent agreement between calculations and field measurements of the tropospheric NO_x[1] photostationary state, (2) an explanation of the formation of atmospheric acetic acid which is verified by field measurements, and (3) calculations of stratospheric ozone perturbations arising from the heterogeneous chemistry of sulfuric acid aerosols during past volcanic periods.

- Refinements to the HO_2/RO_2 "chemical amplifier" following field tests during the Rural Oxidants in the Southern Environment (ROSE) experiment for the first time enable continuous day and night measurements of these key radicals. This instrument is being developed for next year's GTCP field study, the second Mauna Loa Observatory Photochemistry Experiment (MLOPEX II), which will enable tests of photochemical theory and determine whether changes to the tropospheric OH production are affecting its oxidation potential.

- One of two field studies this year focused on the Canadian wetlands and their importance to the global carbon cycle. Projected warming should have the greatest effect on these peatlands, which constitute the world's largest carbon repository. These

---

[1] For names of chemical symbols used in this chapter, see the list on p. 26.

studies are the precursor to future Atmosphere/Ecosystem Gas Interchange Study (AEGIS) projects, which will focus on these fluxes and their potential impact on global warming.

- The first dynamic flow tube measurements were made of N_2O_5 reactions on H_2SO_4 aerosols. The fraction of collisions resulting in reaction was higher than expected, giving new clues to the importance of heterogeneous chemistry in atmospheric processes and global change.

- The first measurements of the temperature dependence of chlorofluorocarbon greenhouse gases were made, which should improve the ability of global models to predict the effects of potential tropospheric warming and improve the precision of estimates of the atmospheric concentrations of these gases by infrared absorption spectroscopy.

- Modelers and experimentalists are succeeding in the integration of ecosystem flux, reactive chemistry, and three-dimensional transport models that accurately reproduce the complex biosphere-atmosphere system. Interdisciplinary teams are weaving field and laboratory measurements into predictive computer models that can serve as a foundation for understanding the chemistry of our atmosphere and potential future global changes.

Atmospheric Chemistry of Transient Species Section

The Atmospheric Chemistry of Transient Species (ACTS) Section is headed by Jack Calvert. Two major projects are included in the ACTS Section: the Atmospheric Kinetics and Photochemistry (AKP) Project, Calvert, acting project leader; and the Atmospheric Odd Nitrogen (AON) Project, Brian Ridley, project leader. Both groups have contributed significantly to our understanding of the properties and the atmospheric concentrations of the active nitrogen trace gas species present in the atmosphere.

The AKP personnel have become recognized within the international scientific community as leaders in the study of the kinetic and spectroscopic properties of important trace gas constituents of the atmosphere. Studies during the past year have focused on the determination of the rate coefficients of a variety of previously ill-defined chemical reactions and cross sections for some important reactive species in atmospheric chemistry. Quantitative studies of some reactions of reactive transients on aerosols have been studied in cooperation with Global and Remote Observations Section personnel. The AKP group has active programs of instrument development for the field study of rates of photochemically induced atmospheric processes and the determination of reactive peroxy radical intermediates involved in atmospheric chemistry. The group has participated in large field studies in which direct and continuous measurements of the concentrations of the transient peroxy radical species were made by the AKP personnel.

The AON Project concentrates on the budget and photochemical transformations of odd nitrogen compounds and their interactions with other trace species, including radicals in the troposphere and stratosphere. Odd nitrogen species to a large extent control the efficiency of O_3 production in the troposphere and exert considerable influence on the abundance and cycling of hydroxyl and peroxy radicals which, together with O_3, largely determine the so-called oxidizing capacity of the troposphere.

Atmospheric Kinetics and Photochemistry Project

The AKP Project has engaged in a large variety of both laboratory and field work related to the measurement of concentrations and the study of kinetic and spectroscopic properties of some important reactive transient species involved in atmospheric chemistry. These studies have provided new and important information that is of value in assessing the pathways of chemical reactions in the atmosphere.

Instrument Development: The Measurement of Transient Species. One of the most important tests of the present theory of ozone generation within the troposphere involves the direct measurement of the highly reactive, transient free radical species. The AKP group has been at the forefront of research designed to measure one class of these important oxidizing species, the hydroperoxy (HO_2) and the great variety of organic peroxy radicals (CH_3O_2, $C_2H_5O_2$, in general symbolized by RO_2). These radicals form largely through the reactions of the HO radical with hydrocarbons. For example, CH_3O_2 forms in reaction sequence (1) and (2), while HO_2 is formed in the sequence (3) and (4):

$$CH_4 + HO \rightarrow CH_3 + H_2O \tag{1}$$

$$CH_3 + O_2 \rightarrow CH_3O_2 \tag{2}$$

$$CH_3O_2 + NO \rightarrow CH_3O + NO_2 \tag{3}$$

$$CH_3O + O_2 \rightarrow HO_2 + CH_2O \tag{4}$$

The importance of these radicals is their ability to oxidize NO to NO_2 efficiently. This in turn influences the atmospheric ozone concentration. It is formed from the photolysis of nitrogen dioxide in (5), and the capture of the O atoms by O_2 in (6), and its buildup is limited by ozone removal in (7):

$$NO_2 + h\nu \rightarrow O + NO \tag{5}$$

$$O + O_2\ (+M) \rightarrow O_3\ (+M) \tag{6}$$

$$O_3 + NO \rightarrow NO_2 + O_2 \tag{7}$$

If reaction (7) is the dominant source of NO oxidation, then the concentration of ozone formed will be given approximately by the photostationary state relation (8):

$$[O_3] \approx ([NO_2]/[NO])\ (j_{NO_2}/k_7) \tag{8}$$

where k_7 is the rate coefficient for reaction (7). It can be noted in this relation that the $[O_3]$ is directly proportional to the $[NO_2]/[NO]$ ratio. That is, as the $[NO_2]/[NO]$ ratio increases in the troposphere, the $[O_3]$ level increases. The reactive transient HO_2 and RO_2 radicals formed in the atmosphere drive NO to NO_2 through reaction (3) and other similar reactions involving the other RO_2 species; hence the ozone levels are expected to increase as suggested in the relation (8). The theoretical expectations described here can be tested from the data derived by some recent AKP studies. During the past year the AKP group developed and employed in the field a new calibrated instrument for the measurement of the important peroxy radicals in the atmosphere. This was employed successfully in the ROSE experiments carried out during June and July 1990 in the pine forests of Alabama (Christopher Cantrell, Richard Shetter, John Lind, and Calvert). Continuous measurements (day and night) of the $[HO_2] + [RO_2]$ sum were made during this period, and important tests of the theory of the involvement of these radicals in the chemistry of the atmosphere can now be made. During the ROSE studies, simultaneous measurements were made by other research groups from NCAR, NOAA, and other laboratories of the concentrations of NO, NO_2, O_3, hydrocarbons, and their oxidation products. A variety of experimental tests of the theories of HO and peroxy radical involvement in ozone generation will be possible using this important new set of data. Work continues within AKP (Cantrell, Shetter, Curtis Gilliland, and Calvert) to improve the instrument to monitor peroxy radicals for use in the planned MLOPEX II study to be carried out at Mauna Loa during 1991 and 1992.

The rate with which the important HO radicals are formed in the atmosphere in theory controls the many oxidation reactions which occur within the atmosphere; for example, hydrocarbon oxidation, peroxy radical generation, etc. Shetter, Cantrell, Gregory Kok, and Calvert have designed and are constructing instrumentation which will allow a direct measure of the ozone photolysis rate in the atmosphere. HO radicals are produced in (10) following the ozone photolysis in (9):

$$O_3 + h\nu \rightarrow O(^1D) + O_2 \tag{9}$$

$$O(^1D) + H_2O \rightarrow 2HO \tag{10}$$

This new instrument, coupled with that for HO_2/RO_2 radical measurements which is actively under development, will allow for the first time reasonably accurate estimates of both the rate of HO radical generation and the HO_2 and RO_2 concentrations in the MOPLEX II experiments. New and important tests will be made of current theories of HO and peroxy radical involvement in the atmospheric chemistry.

A research team composed of AKP personnel (Kok, Shetter, and Cantrell) and staff from the Atmospheric Technology Division (ATD) is involved in the development of j_{NO_2} and j_{O_3} instrumentation for use on NCAR research aircraft. Tests of current theories of cloud enhancement and attenuation of the j values are planned.

Chemistry of Reactive Nitrogen Species; Gas-Phase Kinetic Studies. Several laboratory studies carried out by the AKP personnel have helped to derive some of the ill-defined kinetic properties of the NO_3 free radical, a species of importance particularly in the nighttime atmosphere. The rate coefficients for the reaction

$$NO_3 + NO_2 \rightarrow NO + NO_2 + O_2 \qquad (11)$$

were determined relative to that for

$$NO + NO_3 \rightarrow 2NO_2 \qquad (12)$$

(Cantrell, Shetter, Anthony McDaniel [University of Colorado], and Calvert). The temperature-dependent function for the rate constant ratio was derived: k_{12}/k_{11} = 387 exp (-1375/T). These data, when coupled with those for k_{12}, provide a new estimate for k_{11}; the new rate coefficient is approximately a factor of two smaller than previous estimates. This reaction is the only recognized nighttime source of NO in the atmosphere. NO reacts with O_3, and hence reaction (11) helps establish the nighttime levels of O_3. In other experiments the important rate constant for the association of NO_3 with NO_2,

$$NO_3 + NO_2\ (+M) \rightarrow N_2O_5\ (+M) \qquad (13)$$

was studied using a discharge flow tube experiment with laser-induced fluorescence of the NO_3 radical for detection (John Orlando, Geoffrey Tyndall, Cantrell, and Calvert). Kinetic parameters, derived from experiments over a range of temperatures (236 to 358 K) and pressures of nitrogen (0.5 to 8 Torr), allow a more quantitative description of the NO_3 and N_2O_5 concentrations in the upper troposphere and lower stratosphere. A complimentary study of the reverse of reaction (13) was made (Cantrell, Shetter, Calvert, Tyndall, and Orlando) over a large temperature and pressure range using Fourier transform infrared analysis to follow the reaction

$$N_2O_5\ (+M) \rightarrow NO_3 + NO_2\ (+M) \qquad (14)$$

The combined data from these studies provides a new estimate of the rate constant ratio, k_{14}/k_{13}, which is equal to the equilibrium constant K for the reaction, $N_2O_5 \leftrightarrow NO_3 + NO_2$. These data provide a quantitative check between rate data and equilibrium data for the N_2O_5-NO_3-NO_2 system and should allow reasonably accurate simulations of the upper atmospheric concentrations of NO_3 and N_2O_5 to compare with recent satellite measurements.

Coleen Roehl (Advanced Study Program graduate research assistant) initiated new studies using laser excitation of NO_2 within the energy-deficient region of the NO_2 photodissociation. This work will provide the necessary quantum yield and absorption data to test current theories which attempt to explain the nature of the processes and the temperature dependence of them.

In additional rate studies, Tyndall, undergraduate research assistant Karen Nickerson (Colorado College), Orlando, and Calvert studied the rate constant for the reaction of NH_2 radicals with oxygen. The new lower limit estimated in this work excludes the direct oxidation of NH_2 by O_2 as an important source of oxides of nitrogen or other products; reactions with NO_2, NO, and O_3 are shown to be much more significant in the atmosphere. Further studies by Tyndall, Orlando, and Calvert have provided a new upper limit estimate for the possible atmospheric reaction, $HO_2 + NO_2 \rightarrow HONO + O_2$. This reaction, suggested to be a possible important source of HONO during the nighttime hours, appears to be unimportant. Tyndall, Orlando, Cantrell, and Calvert made additional kinetic studies of the possible ozone destruction reaction, $CH_3O_2 + O_3 \rightarrow CH_3O + 2O_2$. Although the somewhat analogous reaction of ozone with HO_2 radicals is important in the atmosphere, the new data prove the unimportance of the CH_3O_2 reaction for atmospheric conditions.

Spectroscopic Studies. Recent AKP studies (Orlando, Tyndall, Nickerson, and Calvert) will provide useful new spectroscopic data related to the collision-induced infrared absorption bands in oxygen. The studies, made over a wide range of pressures and temperatures applicable to atmospheric conditions, provide the necessary data to allow correction of the oxygen absorption that occurs in the infrared spectra of many trace gases obtained by remote sensing satellites. Other infrared spectral studies related to the commonly used halocarbons were carried out by Cantrell, McDaniel, Shetter, and Calvert; these data will be very useful in the estimation of greenhouse effects and in concentration estimates from atmospheric absorption data.

The Kinetics of Heterogeneous Chemistry. In a team effort involving Alan Fried, Bruce Henry, Calvert, and Michael Mozurkewich (York University, Canada), studies of reactive molecules with sulfuric acid aerosols are in progress. The combination of laser diode spectroscopic techniques for product and reactant analysis with techniques for monodispersed aerosol generation and monitoring has provided improved accuracy in the determination of the fraction of the collisions of gaseous N_2O_5 with H_2SO_4 aerosols which result in nitric acid generation. Modeling studies in the Atmospheric Chemical Modeling (ACM) Section using data developed in these studies suggest the probable significance of N_2O_5-sulfuric acid aerosol reactions in influencing ozone levels in the stratosphere.

Atmospheric Odd Nitrogen Project

The AON Project emphasizes (1) the development of instrumentation for measurements of organic and inorganic odd nitrogen and other trace species in the remote atmosphere; (2) aircraft, balloon, ship, and ground-based field measurement programs; and (3) through collaboration with other ACD sections, the analysis and interpretation of experimental observations.

Field Studies. (a) MLOPEX results. Over the past year, a substantial effort was made to analyze and interpret results obtained from the first Mauna Loa Observatory Photochemistry Experiment (MLOPEX) conducted in the spring of 1988 in collaboration with scientists from the University of Rhode Island, University of Colorado (CU), Drexel University, Texas A&M University, NOAA Climate Monitoring and Diagnostics (CMD) and Aeronomy laboratories, and ACD. (See last year's *Annual Scientific Report* for a listing of the personnel involved in the experiment.) MLOPEX I participants and colleagues recently submitted 14 manuscripts to appear as a group in the *Journal of Geophysical Research.* Several of these manuscripts highlighted the intercomparison of observations and the results of models developed by Sasha Madronich and Shaw Liu (NOAA Aeronomy Laboratory). A few highlights of MLOPEX follow.

- Although the timing of MLOPEX was close to the maximum in transport of Asian dust to the region, there were no clear-cut signatures of reasonably direct continental influence in the measurements. Isentropic back-trajectories showed origins over the Pacific Rim or southern North America several times during the experiment, but these occurrences were 8–10 days prior to the measurement. Longer-term variations on the order of a few days to a week or more in some of the trace species were attributable to transport from equatorial regions and lower altitudes versus transport from northern latitudes and perhaps higher altitudes. Ultimately, of course, transport from continental sources or the stratosphere must account for the latitude gradients implied from the observations.

- Measured NO_2/NO ratios showed very good agreement with the results from a detailed photochemical box model that was constrained by measured O_3, j_{NO_2}, and other parameters. The implied abundances of peroxy radicals from the observations were then in good agreement with the model. However, the implied concentration of OH is larger than suggested from earlier aircraft flights in the Pacific region.

- A comparison of measured and calculated H_2CO, HOOH, ROOH, and NO_x/HNO_3 with model calculations also suggests that photochemical models of the remote atmosphere overestimate the OH abundance. Similar conclusions have been reached by Dieter Perner and colleagues (Institute for Atmospheric Chemistry, Jülich, Germany) for continental Europe, a regime of atmospheric chemical loadings very different from the Pacific region. If models are accurate, then some of the measurements made during MLOPEX may have larger uncertainties than estimated. If measurements are accurate within their stated uncertainties, then model assumptions may be in error. Because the implication is so fundamental to atmospheric chemistry globally or regionally, further research is necessary.

- The NO_x measurements and model runs for conditions of the MLOPEX experiment show that net photochemical destruction of ozone occurs in free tropospheric air masses. This was also true during upslope flow conditions even though the upslope flow of marine boundary layer air is perturbed by island sources of O_3 precursors. In both flow regimes the daily net photochemical loss was not very large, ~1 ppbv/day.

- In the free troposphere, the sum of concentrations of HNO_3, NO_3^-, alkyl nitrates, PAN and analogs, and NO_x was an average of 25% less than total odd nitrogen, NO_y, determined using the gold/CO catalyst technique developed at the NOAA Aeronomy Laboratory. The 25% shortfall in the odd nitrogen budget is similar to some observations in continental regions. At Mauna Loa, HNO_3 was the most abundant odd nitrogen species, but measured organic nitrates were a relatively small fraction of NO_y. In general, the partitioning of odd nitrogen was roughly as expected from model estimates. The presence of the odd nitrogen shortfall in remote regions raises questions about our understanding of the odd nitrogen budget.

(b) MLOPEX II preparations. The section has also led the planning and development of the second phase of the Mauna Loa Experiment (MLOPEX II) scheduled for implementation in 1991 and 1992. This program is designed as an extension of the 1988 experiment, builds upon its experimental and modeling experience, and is designed to obtain measurements of a wide variety of photochemically active trace species over an annual cycle. A document describing its objectives within the NSF GTCP and its relation to several activities of the International Geosphere-Biosphere Program's International Global Atmospheric Chemistry (IGAC) has been circulated internationally by the steering committee (Elliot Atlas, Ridley, Guy Brasseur, Calvert, Madronich, and Patrick Zimmerman of NCAR; Liu, Fred Fehsenfeld of the NOAA Aeronomy Laboratory; Brian Heikes of the University of Rhode Island; Eldon Ferguson of NOAA CMDL; and Mary Anne Carroll and Jarvis Moyers of NSF).

(c) SAGA-III. Atlas continued his investigation of the distribution of organic nitrates in the remote atmosphere by participating in the Joint Soviet-American Gas and Aerosol Experiment (SAGA-III) research cruise in the equatorial Pacific. Air samples were collected by Anne Thompson (NASA Goddard Space Flight Center) and analyzed at NCAR by Atlas. The organic nitrates measured, chiefly alkyl nitrates, are reservoirs of active odd nitrogen and their significance to the budget of odd nitrogen needs to be determined geographically and seasonally.

(d) Balloon flights. Andrew Weinheimer and Frank Grahek spent a considerable effort in June at Palestine, Texas, preparing the stratospheric nitric oxide instrument for a joint balloon flight with Harvard University (Elliot Weinstock and James Anderson, principal investigators). The first attempt had to be delayed due to difficulties Harvard experienced with their laser power supply. ACD personnel returned for a second attempt in August, but further problems with the very complex Harvard instrument delayed a launch attempt again. In early September, all instruments were ready to fly, but poor weather scrubbed one attempted flight, and shortly thereafter the reversal of the stratospheric winds prevented further launch attempts for the year.

(e) ROSE experiment. James Walega, Atlas, Lind, Ridley, and Thaddeus Sauvain participated in the ROSE experiment, organized by the NOAA Aeronomy Laboratory (Fehsenfeld, David Parrish, Michael Trainer, and colleagues). This experiment investigated regional/rural ozone formation in a part of the U.S. that experiences high sunshine levels, high temperatures and water vapor, and high emissions of natural nonmethane hydrocarbons (NMHC). Its goal was to answer the following questions: (1) Which precursors limit ozone production, the oxides of nitrogen or NMHC? (2) Are biogenic or anthropogenic NMHCs more important in regional ozone production? (3) How important is regional-scale photochemical production of ozone compared to local production in leading to ozone levels that exceed air quality standards? In collaboration with Gerhard Hübler (NOAA/CU) and Alan Schanot, Herminio Avila, Michael Heiting, and Henry Boynton (Atmospheric Technology Division), the AON participants used the Sabreliner aircraft to determine the regional and vertical (100–16,000 feet) distribution of O_3, NO_y, NO, NO_2, alkyl nitrates, NMHCs, and meteorological state parameters. Eleven flights were made from the base in Meridian, Mississippi, during the last two weeks of June. O_3 and odd nitrogen measurements were continuously made in situ during the flights using high sensitivity instrumentation previously developed by the section for light aircraft studies. Periodically, spot samples were collected during the flights for laboratory analysis of the alkyl nitrates, and canisters were collected for NMHC analysis by Eugene Allwine and Halvore Westberg (Washington State University). Lind worked with Shetter, Cantrell, and Calvert at the ground-based site in Alabama to determine the abundance and behavior of peroxy radicals using their radical amplifier technique. Data analysis, interpretation and modeling for the experiment is ongoing.

Instrument Development/Laboratory Studies. The following work was carried out in FY 90:

- The stratospheric nitric oxide instrument was modified to improve flow measurement accuracy, a new data acquisition system was constructed and tested, and the complete instrument calibrated ready for the summer flight.

- A new thermal desorption technique for analysis of organic nitrates was developed. Using this and the previous adsorption technique, Atlas has worked with Cantrell and colleagues in the AKP project and Thomas Ryerson and Robert Barkley (CU) to characterize the kinetics and products of reactions of alkenes with N_2O_5 using gas chromatograph (GC)/electron capture detector (ECD) and GC/mass spectrometer (MS) techniques.

- Lind and Atlas, building upon previous work by Bruce Gandrud and Heikes, modified the sampling and analysis procedure for a rapid (10–15 min) determination of ambient nitric acid and particulate nitrate using an ion chromatograph. The instrument was tested with sulphate particles to determine particulate sampling efficiencies in collaboration with Fried and Henry. This work is directed towards more frequent measurements of nitric acid during the MLOPEX II experiment.

- Lind used the ion chromatograph to determine bromide in a number of filter samples for William Sturgis at the University of Colorado.

- Walega and Bryan Lee developed new, compact data acquisition systems for the aircraft and balloon instruments.

- Grahek, Ridley, and Walega continued to develop the chemiluminescence instruments to improve sensitivity and performance for remote atmosphere observations. A new suite of instruments is being designed and constructed for the MLOPEX II project.

- In conjunction with Shetter, AON is directing the modification of sea containers to house the MLOPEX II instrumentation, and to provide a "portable" suite of instrumentation from ACD for future field projects.

Global and Remote Observations Section

During fiscal year 1990, the Global and Remote Observations (GRO) Section, under the leadership of John Gille, consisted of the Global Observations and Modeling (GOM) Project, led by Gille, and the Optical Techniques (OT) Project, headed by William Mankin.

GRO's goals are to obtain observations of atmospheric structure and composition in order to understand chemical processes and the ways in which they interact with the dynamics and energetics of the atmosphere. Observations are obtained by in situ and remote sensing optical techniques, employed from the ground, aircraft, and satellites.

Global Observations and Modeling Project

Activities in the Global Observations and Modeling (GOM) Project range from the development and flight of satellite instruments for observing the atmosphere through the reduction of the measurements to geophysical quantities and subsequent interpretation of the results. Present work extends from the surface to the mesopause, broadening an earlier emphasis on the stratosphere and low mesosphere.

Analysis and Interpretation of Global Data. Two studies of tropical Kelvin waves were carried out, following the investigation by William Randel (1990) described in last year's report. Those results used the seven months of data from the Limb Infrared Monitor of the Stratosphere (LIMS), which have high vertical resolution and several constituents, to show the Kelvin wave–induced fluctuations in O_3 and other trace gases. The newer studies are based on over eight years of Solar Backscatter Ultratiolet (SBUV) O_3 observations, mapped at NCAR using a Kalman filter technique. A study by Isamu Hirota and colleagues at Kyoto University, working with Gille, showed clear evidence for equatorially trapped Kelvin waves above 10 mb, having an eastward migration period of about seven days. The study considered the effect of the quasi-biennial oscillation (QBO) in the tropical lower stratosphere on the vertical propagation, which in turn allows the QBO to modulate the mean field in the upper stratosphere. Randel and Gille critically analyzed the same SBUV data, using the period of overlap with LIMS as a validation period. There is reasonable agreement between the analyzed waves from 5 to 0.5 mb, although SBUV amplitudes are smaller, and the vertical wavelengths are too large. They conclude that the Kelvin wave is at best a small source of westerly momentum to the semiannual oscillation (SAO), in agreement with other work.

Randel and Leslie Lait, NASA Goddard Space Flight Center (GSFC), completed an observational study of the four-day wave, a regularly propagating planetary wave feature observed in the winter upper stratosphere. Horizontal winds derived from satellite radiances in the upper stratosphere show direct evidence of a barotropic instability source mechanism: the zonal mean flow is found to be barotropically unstable, and eddy flux signatures demonstrate in situ barotropic growth of the wave.

A study of the wave number–phase speed spectral decomposition of tropospheric eddy heat and momentum fluxes, and Eliassen-Palm flux divergences, was carried out by Randel and Isaac Held (Geophysical Fluid Dynamics Laboratory). The idea of this analysis was to test idealized models of transient wave-critical layer interactions against observations, in this case global analyses from the European Center for Medium-Range Weather Forecasts (ECMWF). The results demonstrate that upper tropospheric eddies break and decelerate the zonal flow 10–20° in latitude away from the critical line (where the wave phase speed equals the zonal wind speed). Results were also calculated from circulation statistics at 10 mb in the middle stratosphere. Southern Hemispheric eddies show remarkable alignment near the critical latitude, whereas Northern Hemispheric waves do not. The difference is probably due to the small amplitude of Southern Hemisphere waves, whose behavior is therefore more closely approximated by linear theory.

Development of New Observational Techniques. A major activity during this period was work on the detailed definition of the High Resolution Dynamics Limb Sounder (HIRDLS). The U.S. investigators, Gille (principal investigator, or PI), Paul Bailey, Byron Boville (Climate and Global Dynamics Division, or CGD), Brasseur, Michael Coffey, and Mankin of NCAR, and James Holton and Conway Leovy (University of Washington), reached agreement with a group of investigators from Oxford University led by John Barnett to combine efforts on a collaborative experiment. The instrument will be jointly produced in the United States and the United Kingdom, and the two teams will merge and cooperate on the complete experiment and data use. The instrument will have improved horizontal and vertical resolution and a greater ability to observe the lower stratosphere than previous observing systems. The experiment's goals are to obtain measurements that will allow much improved understanding of the flow of mass and constituents between the troposphere and stratosphere, the chemical processing of trace constituents, the momentum and heat budgets (including the previously unobserved small-scale dynamical and mixing processes in the middle atmosphere), and interannual variability and trends. The definition studies produced detailed plans for the development of the instrument and its subsystems, and the data reduction. The instrument has the capability to measure temperature, O_3, H_2O, CH_4, N_2O, NO_2, N_2O_5, HNO_3, F-11, F-12, and $ClONO_2$ with the required precision and accuracy.

Design studies were also carried out for a second experiment with GRO involvement, the Measurement of Pollutants in the Troposphere (MOPITT). This experiment was proposed by James Drumond (PI, University of Toronto), with Gille, Brasseur, John McConnell (York University) and Guy Peskett (Oxford University). The objectives are to measure the vertical distribution of CO in the troposphere, using a new radiometric device, and to use the results with models to improve understanding of tropospheric chemistry. Canada will be responsible for the development of the instrument, while GRO will develop the data-reduction software. Again, detailed plans for the instrument and data reduction were produced. These included a more detailed assessment showing an ability to determine profiles in the troposphere under clear conditions to about 10% or less, with a vertical resolution of about 3 km.

In a much nearer time frame, Gille, Bailey, and Steven Massie are continuing preparations for the launch of the Upper Atmosphere Research Satellite (UARS), scheduled for the second half of 1991. Major effort continues on the development of algorithms for the inversion of data from the Cryogenic Limb Array Etalon Spectrometer (CLAES) experiment. A key requirement is the calculation and parameterization of atmospheric transmittances needed in the retrievals. Massie and David Edwards (visitor, Oxford University) have greatly increased the speed of two codes to calculate high-resolution absorption coefficients, including the effects of line-mixing and non-Lorentzian line shapes. These were then used to calculate instrumentally averaged transmittances, and efforts are now under way to express these as accurate and fast parameterizations.

Gille and Massie are also leading a comparison among the different basic transmittance codes used by the UARS Science Team. Initial calculations led to the identification and correction of some errors of a few percent. This reduction of correctable differences now will lead to a faster and more confident validation of the UARS results. Bailey and Daniel Packman continued to provide assistance in the planning and implementation of the UARS Data System.

In collaboration with Curtis Rinsland (NASA Langley Research Center) and Aaron Goldman (NCAR affiliate scientist from the University of Denver), Massie participated in a study of the long-term trends in the concentrations of SF_2, $CHClF_2$, and COF_2 in the lower stratosphere. This study shows that the mixing ratio of F-22 increased by nearly a factor of two between 1981 and 1988. Massie has also contributed analyses of cold temperature cross sections for eight CFCs for the next infrared spectral data bases.

Massie also participated in the analysis of balloon-borne spectra with Miam Abbas (NASA Marshall Space Flight Center) and Virgil Kunde (GSFC)and colleagues at NASA to provide the first direct determination of the nighttime total reactive nitrogen concentrations and the partitioning of the members of the NO_x family (NO_2, N_2O_5, HNO_3, and $ClONO_2$).

Optical Techniques Project

The goals of the Optical Techniques (OT) Project remain the use of optical methods for studying the chemistry of the atmosphere and the development of optical instruments and techniques for such studies. Emphasis within the project has been on the chemistry of the stratosphere, but work has also been undertaken on tropospheric instrumentation.

Stratospheric Ozone Studies. Mankin and Coffey participated in the 1987 Airborne Antarctic Ozone Experiment and in the 1989 Airborne Arctic Stratospheric Expedition, both aimed at investigating the perturbations to stratospheric chemistry in the polar winter and the resulting changes to ozone. They recorded over 10,000 high-resolution infrared atmospheric absorption spectra from which column amounts of many stratospheric trace gases may be determined. They published a case study of one day's observations in the Arctic when measurements were made crossing the boundary of the polar vortex. There was a very significant correlation of stratospheric composition with position relative to the vortex boundary. The results showed that during the polar winter the processes that release active chlorine from the reservoirs proceed in the Arctic much as they do in the Antarctic stratosphere. In particular the conversion of HCl by heterogeneous chemistry occurs to almost the extent that it does over Antarctica. There are significant differences between the polar regions in the extent of removal of odd nitrogen compounds. The fact that a major ozone hole does not occur in the Arctic is attributed to the breakup of the polar vortex before the springtime return of sunlight to drive the photochemistry.

Mankin and Coffey analyzed the data from the other flights in the Arctic region as well, and supplied the data to the archive for use by other investigators. They are refining the analyses of these data and, with Mark Abrams (visitor from the University of California, Berkeley), are working to resolve a systematic difference between their results and those of another group for two compounds. They are continuing the analysis of the data in terms of the meteorological situation and temporal evolution of the vortex during the period of the experiment.

In related work, Fried and Henry measured the rates of chemical reactions on the surface of stratospheric aerosol particles. Heterogeneous processes, which had not generally been included in stratospheric chemical models before the discovery of the ozone hole in 1985, play a dominant role in the polar regions in winter and may affect the ozone layer on a global scale. In particular, Fried and Henry are investigating the reaction of the nitrogen reservoir compound N_2O_5 on the sulfate aerosols that occur globally in the lower stratosphere and are greatly enhanced after major volcanic events. Preliminary results indicate that the reaction rate is sufficiently high that this reaction could be a significant part of the stratospheric chemistry following major eruptions. This is in accord with measurements by Coffey and Mankin of a reduction of NO_2 in the plume of the El Chichón volcano in 1982. Fried and Henry are extending their measurements to lower temperatures and later plan to measure the rate and products when $ClONO_2$ reacts on sulfate aerosols.

The rapid development of the ozone hole and the trend in midlatitude ozone determined by the Ozone Trends Panel highlight concerns over the changing composition of the stratosphere. With their database of over 20,000 spectra dating back 12 years, Mankin and Coffey are in a position to measure the rates of change of several stratospheric species. Earlier they published rates of change of HCl and HF in the stratosphere, due mostly to release of CFCs. They are refining these rates based on additional data and a more refined analysis of the spectra using nonlinear least squares fitting. It has also been suggested that carbonyl sulfide (OCS) is increasing with time; this suggestion is based on observed increases of sulfate aerosols during volcanically quiet times. From the spectra, Mankin and Coffey can test this suggestion; preliminary work indicates a rate of increase of less than 1% per year compared with the hypothesized 5% per year. Coffey has been doing some of the analysis while on sabbatical leave in England. Fried has developed the capability of high-precision OCS measurements with tunable infrared diode lasers and is making measurements in the lower atmosphere aimed at determining sources of OCS and whether they are changing as a result of human activity.

Mankin, Coffey, and Abrams have begun work on extending their various spectral measurements to include all four seasons so that seasonal effects can be removed and spurious apparent trends avoided.

The OT group is participating in a larger effort to determine long-term trends in the stratosphere. The Network for Detection of Stratospheric Change (NDSC) is an international program to use ground-based high-precision measurements of stratospheric composition and physical state along with global satellite measurements to provide early detection of changes in the stratosphere. Each of half a dozen ground-based sites will have lidars and spectrometers ranging from ultraviolet to microwave. NCAR expects to supply the infrared spectrometer for one of the sites. In addition, the group will make available its airborne spectrometer for flight between different stations to intercompare instruments. Such instrument intercomparison is a critical element of the NDSC experiment design. Mankin is serving on the Steering Committee for the NDSC and chairs the working groups on infrared measurements and site selection.

Mankin and Coffey have participated in the planning of the next polar missions. The planning process has defined the goals of the missions and helped with operational decisions.

Tropospheric chemistry. David W.T. Griffith (visitor, University of Wollongong, Australia) and Coffey conducted a program of field measurements of chemical effects of biomass burning in cooperation with the U.S. Forest Service. They used the Fourier transform spectrometer in a long-path mode with an infrared source located up to 200 m away and observed the composition of the intervening air during a brush or forest slash fire. In addition to the measurements in open fires, Griffith studied the production of various gases in controlled laboratory fires in a Forest Service laboratory. The results provided information on the production of combustion species during various phases of the burn. In particular, an unexpectedly high concentration of ammonia was measured during the low-oxygen smouldering phases of the fires.

Coffey participated in the planning of future GTCP campaigns, especially the AEGIS program to measure fluxes of chemically active gases to and from various ecosystems. He and Mankin are working to adapt their earlier CO laser instrument to measure methane fluxes by the eddy correlation method. They expect to use this instrument in AEGIS field measurement programs.

Biosphere–Atmosphere Chemistry Section

In 1990, the Biosphere-Atmosphere Chemistry (BAC) Section placed emphasis on collaborative research among scientists in the section, rather than on individual projects. The research focus of the section remains the same: to develop an understanding of trace gas fluxes and their relationships to atmospheric chemistry, biogeochemical cycles and global change. The strategy to accomplish this research includes the identification and classification of atmospheric biogenic emissions and their photolytic products; development of the technology to facilitate measurements of the distributions and fluxes of chemically and/or radiatively important trace gas species; laboratory studies to isolate and identify limiting emission processes and potential interactions and feedbacks; and finally, integration of this information into models that can predict emissions on local, regional and global scales. This research is a necessary prerequisite to an understanding of the chemical dynamics of the atmosphere, and realistic predictions of the consequences of global change on future climate.

AEGIS

The Atmosphere/Ecosystem Gas Interchange Study (AEGIS) is an initiative under the GTCP, which addresses several issues judged to be critically important by the IGAC committee within the International Geosphere Biosphere Program. Planning meetings and workshops held during 1989 identified the boreal forest region as the initial target of study. This area was chosen for several reasons: (1) The boreal forest occurs over much of the globe at high latitudes; (2) the atmospheric chemistry of these remote continental regions has been largely unexplored and contains huge amounts of stored carbon in the form of peat; (3) it is an area projected to be greatly impacted by future global warming; and (4) feedbacks between global warming and carbon storage and cycling could potentially be large. In addition AEGIS will allow NCAR and university collaborators to interface with other planned research programs, such as the Boreal Ecosystem-Atmosphere Study (BOREAS) program of NASA.

Northern Wetlands Field Study

Some of the methodologies that are to be used to investigate methane fluxes during AEGIS were tested in 1990 during participation in the Canadian Northern Wetlands Study (NOWES) conducted in Northern Ontario. This study, led by the Canadian Institute for Research in Atmospheric Chemistry, was a collaborative effort by numerous Canadian universities and U.S. agencies. The BAC effort in NOWES included the establishment of walkways and measurement enclosures along an ecological transect extending from the coast of James Bay inland to Kenosheo Lake, a distance of about 70 km. In addition, an analytical laboratory was set up in Moosonee for analysis of specific trace gases. The BAC Section also provided precise analysis of eddy accumulator samples (a micrometeorological flux technique developed by Raymond DesJardines, Agriculture Canada) collected aboard the Atmospheric Environment Service twin Otter research aircraft. The field measurement program extended from June until August with an additional one-week measurement program in October. Field measurements were coordinated by Lee Klinger (Advanced Study Program, or ASP, postdoctoral fellow) with participation of Gillian Walford and David Goldbloom (research assistants from CU) and other BAC staff. Laboratory measurements were coordinated by Leroy Heidt and James Greenberg, and many of the analyses were performed by Curtis Gilliland (visitor). Other BAC staff that participated in the field portion included Richard Lueb and Zimmerman. Selected enclosure and ambient air samples were returned to the Boulder laboratory for determination of fluxes of NMHCs, N_2O, and other trace gases. Samples were also collected for analysis by Stanley Tyler to determine the isotopic composition of the methane carbon. This analysis will provide data that will aid in understanding the sources and processes controlling methane emissions.

Detailed ecological measurements were coordinated with gas measurements at each sampling site. These included species composition and abundance, leaf and root biomass, soil moisture chemistry, and peat cores. Cores were shipped to NCAR for studies to determine methane generation potential and isotopic fingerprints (in collaboration with David Schimel and David Valentine, Colorado State University, or CSU).

ROSE Field Study

The BAC Section also participated in the ROSE study (as previously described in the AON section). Their field participation extended from 22 June to 22 July 1990 and contributed to the experiment in several ways: they (1) conducted an initial biomass inventory of the site to determine the primary vegetation species for intensive field study; (2) conducted extensive enclosure measurements to determine hydrocarbon fluxes from the dominant vegetation types; (3) operated a field analytical laboratory for routine trace hydrocarbon measurements; (4) operated a gas chromatograph/mass spectrometer (GC/MS) system to identify specific vegetation hydrocarbon fingerprints and to confirm identities of ambient hydrocarbons; (5) designed, built, and used a tethered-balloon sampling system to measure vertical profiles of meteorological variables and hydrocarbons to 500 m; and 6) collaborated with Washington State University (WSU) to measure hydrocarbon fluxes using an SF_6 tracer system.

The experiment integrated many facets of BAC research. For example, the biomass inventory, largely assembled by Walford, utilized her skill in the interpretation of remotely sensed data and geography. Alex Guenther (joint NCAR/CU/NOAA postdoctoral fellow) conducted enclosure measurements of physiological parameters such as carbon dioxide uptake and transpiration rates in addition to measurements of isoprene and terpene fluxes. These data allowed the extrapolation of field rates to other conditions of light and temperature using algorithms derived by Guenther, Raymond Fall, and Russell Monson (both from CU) based on laboratory studies using a fast isoprene detector developed by Alan Hills and Zimmerman. In addition, the enclosure samples were analyzed using a gas reduction cell first applied to the analysis of isoprene and modified by Curtis Westberg (unaffiliated visitor) to include terpene analysis while on sabbatical at NCAR. The GC/MS analyses (by Walter Pollock) and the hydrocarbon profiles (by Zimmerman, Greenberg, William Bradley, and Marisa Kadavanich (student visitor, Metropolitan State University)) utilized technology developed over several years in the BAC section. The tracer studies (Zimmerman, Brian Lamb [WSU], and Westberg) were built on previous research experience in Scotia, Pennsylvania, and an ongoing collaboration with WSU. Lueb and Heidt also participated in preparations for the field campaign.

Tropical Deforestation and Trace Gas Emissions

Global change is accelerating in the tropics. Tropical deforestation is occurring at an unprecedented rate. The tropics, with approximately 40% of the earth's land area, account for 69% of terrestrial net primary productivity. In addition, because of warm temperatures and high rainfall, nutrient cycling often occurs at high rates. The impacts of deforestation on the production of trace gases are currently little understood. The BAC is therefore participating in a collaborative study with William Reiners (University of Wyoming), the Organization for Tropical Studies at the La Selva Field Station in Costa Rica, and Michael Keller (ASP postdoctoral fellow) to determine the impact of the conversion of tropical forest to pasture on emissions of methane, nitrous oxide and nitric oxide emissions. The research program will include field measurements and laboratory measurements of the isotopic fingerprints of methane carbon as well as experiments to determine the isotopic fractionation of methane during its oxidation in the soil. These measurements will be carried out by Tyler and Gordon Brailsford (Institute of Nuclear Sciences,or INS, Lower Hutt, New Zealand) in the stable isotope lab of BAC. The research is being supported jointly by NSF (Ecosystem Studies) and the Environmental Protection Agency (EPA).

Methane Studies

The atmospheric mixing ratio of methane is increasing annually at the rate of nearly 1%. Reactions of methane with hydroxyl radical help to control the oxidant balance of the troposphere. Methane is also an important greenhouse gas with an atmospheric lifetime of seven to ten years. Although the sources of methane emissions to the atmosphere are thought to be primarily biological, the fluxes of methane from these sources are poorly known, and knowledge of the feedbacks of future global change on methane fluxes is almost nonexistent. The BAC section has therefore focused on studies to improve our ability to make methane flux measurements, studies of fluxes from the major methane sources, and the development of predictive methane flux models.

The BAC group in cooperation with NCAR's Atmospheric Technology Division developed a conditional sampler. It can be used to determine fluxes of a wide range of trace gases in addition to methane. The conditional sampling system in conjunction with a sonic anemometer measures the vertical components of turbulence and calculates the sizes of the gusts that are responsible for most of the mass transfer. Typically 5 to 10% of the gusts carry about 90% of the flux. These gusts are then sampled into appropriate sample containers (such as teflon bags for methane) using a series of fast solenoid valves and a small pump. One container is used for the "up" gusts, one for the "down" gusts, and one for neutral conditions. Samples collected over a period of about one-half hour can then be taken to the laboratory and analyzed using any equipment with the required sensitivity even though the equipment may have a slow response (such as conventional gas chromatographs for methane). The conditional sampler has been built and initial tests are encouraging. Additional testing will be conducted during 1991.

For many types of sources, methane emissions are dominated by "hot spots" or relatively small areas with a high emission. A portable real-time instrument is required to identify and investigate these sources. The BAC group has therefore modified a flame ionization detector system (typically used as a gas chromatographic detector) for fast, continuous, portable operation. This instrument is not specific for methane but provides an ideal screening tool. The section will continue to improve the instrument through the development of selective filters. The instrument is fast enough to make eddy correlation flux measurements. An instrument using a similar principle of operation has been previously used by Steven Wofsy (Harvard University) to measure methane fluxes. Wofsy collaborated with BAC scientists in the development of the NCAR system.

Enclosure systems are often the systems of choice for measuring methane fluxes. They are relatively simple to deploy and operate, and they result in methane concentrations that are relatively high and easy to measure. Their chief disadvantages are that they provide a series of point measurements that are difficult to extrapolate, they disturb the site when they are placed in the soil, and they may modify physiologically active variables that may affect fluxes such as carbon dioxide, light, and heat inside of the enclosure. The BAC group is developing a mobile flux box enclosure system that will minimize the limitations of enclosures and still provide many of the advantages. The system utilizes a gas correlation radiometer (GCR), designed and built by Hills, Zimmerman, Gary Hampton (visitor, Hampton Associates), and James Smith (visitor, CU), that will provide selective, real-time measurements of methane, carbon dioxide, and a tracer such as CH_3F. The radiometer will be incorporated as part of an enclosure chamber. In one mode of operation, the chamber will be deployed on a cable spanning above a methane source such as a rice paddy. During operation the chamber will move slowly along the cable, and periodically it will be lowered to the height of the rice canopy. The tracer will then be released at a constant rate into the chamber, and the methane concentration, tracer concentration, and CO_2 concentration inside the chamber will be monitored. The methane flux can be calculated from the ratio of the mixing ratio of methane to the mixing ratio of the tracer. The system should provide the advantages of minimal disturbance, measurements over an extensive transect, and relatively simple real-time fluxes. The GCR has been designed to operate on battery power so battery packs can be utilized that will provide for many hours of continuous operation.

NCAR is collaborating with animal physiologists at CSU (Johnson) and WSU (Kristin Johnson, Lamb, and Westberg) on studies of methane fluxes from cattle. Measurement methodologies are being developed which use internal tracers for free-ranging cattle and external tracers for cattle in concentrated areas such as feedlots. The research is being supported partially by NASA and partially by EPA.

The internal tracer technique will involve feeding an animal a tube containing a tracer such as SF_6. Experiments conducted to date at WSU have shown that the tube will settle to the bottom of the rumen where it will remain. At the end of the tube is a small plastic disc which allows SF_6 to slowly permeate through at a rate controlled primarily by temperature. Since the rumen temperature is constant the permeation rate is constant. The cattle will then be fitted with a small collar containing a miniature sample pump and teflon bag (developed as part of the BAC tethered balloon sampling system). A tube will be extended from the collar to the proximity of the animal's mouth. The collar system will then collect an integrated sample of the animal's respiration which will include methane, carbon dioxide, and the tracer. Since the tracer release rates are known and are constant, the fluxes can be calculated from the ratios of trace gases to SF_6.

In the last 100 years, feedlots to fatten and finish cattle have become increasingly more numerous. External tracers have been developed and used to determine feedlot emissions. The method is similar, only a release system is deployed to release the tracer in the feedlot. Samples are then collected to determine ratios of methane and tracer in the feedlot plume. The system has been used at a feedlot near Purdue University and at a feedlot near Fort Collins, Colorado. Results indicate that emission estimates from the feedlot cattle have been accurate (within the uncertainty of the tracer method). In the next year the BAC group (Zimmerman, Guenther, and Hills) will utilize selected feedlots as test facilities for new analytical equipment such as the fast flame ionization detector (FID) and the conditional sampler.

Isotopic analyses of cattle methane and methane derived from manure have distinct $^{12}C/^{13}C$ ratios. The isotopic composition of methane in ambient air in the region indicated that manure disposal systems may be emitting more than 80% of the methane. This increasingly important methane source has not been included in any global methane budget. The EPA, through ICF Corporation, provided funds to survey several types of feedlot systems to determine relative impacts of cattle and manure handling systems. Zimmerman and Tyler will coordinate the sampling strategy. In addition, Elisabeth Holland will conduct laboratory studies of the controls on the methane generation potential of manure.

One of the main sources of abiogenic methane is leakage of natural gas from processing and distribution systems. Estimates of the rates of leakage range from 0.5% to 15% of production. NCAR is participating with Lamb, Westberg, and Patrick Crill and Robert Harriss (University of New Hampshire), with funding from the Gas Research Institute, to investigate the fluxes from these sources. The research will involve tracer releases in cities and measurement of vertical profiles of methane and the tracer downwind. Isotopic measurements will be made to help identify contributions of biogenic methane.

Methane research within BAC is comprehensive. The scientists in the section have developed new analytical tools and experimental techniques and have focused on potentially important methane sources. In addition scientists in the section are participating in the development of models that can link field measurements to process studies so that meaningful, predictive, global extrapolations can be made.

Ecosystem/Trace Gas Flux Modeling

The coupling of ecosystem models of productivity and carbon cycling with mechanistic models of emission processes has been accelerated in 1990. Holland, Zimmerman, Klinger, and Guenther have all been involved in modeling efforts for methane as well as other biogenically emitted trace gases and the work will continue. The work has been done in close collaboration with the ACM section of ACD.

Holland has been working with Valentine (CSU) on the development of a mechanistic model of methane fluxes. The model will be coupled to an ecosystem model (which is a combination of CENTURY and LINKAGES) to provide regional estimates of fluxes for both methane and CO_2. The model simulates both methane production and oxidation based on soil composition, moisture, and temperature. These are used to calculate substrate availability, oxygen concentration, and carbon cycling. Data for model development have partly been obtained through collaborative laboratory research. AEGIS will provide an excellent opportunity for additional development and testing.

The tundra regions of the globe contain large amounts of carbon stored in permafrost. It is important to understand the potential fate of this carbon with respect to future global warming. In 1990, Claire Waelbroeck (unaffiliated visitor) in conjunction with several BAC scientists (especially Holland) developed a model of carbon cycling in tundra ecosystems. One objective of the project was to develop a model that is sufficiently simple, with few driving variables so that it can perform interactive regional simulations of biosphere/atmosphere exchange. The model includes several submodels as well as nutrient, temperature, and water limitations on photosynthesis. In the future, the model will encompass the boreal forest as well as tundra.

Cynthia Nevison (visitor, Stanford University) and Holland worked on the application of the Osnabruck model, developed by Gerd Esser to investigate carbon cycling, to the emissions of nitrous oxide. The first model exercise will be to simulate the temporal changes in atmospheric N_2O concentrations from 1860 to 1980. The focus will then shift to development of predictive capabilities.

Other model efforts included the coupling of three-dimensional transport models with ecosystem models and trace gas emission estimates. These efforts included work by Jean-Francois Müller (visitor, Belgian Institute for Space Aeronomy, Brussels), John Taylor (visitor, Australian National University, Canberra) and several of the BAC staff.

Other BAC Research

In 1990 laboratory work continued on the interactions of atmospheric pollutants and biogenic emissions. The research was lead by Ennis and Lazrus with participation from other members of BAC. These series of experiments allowed the evaluation of plant-atmosphere relationships from both the perspective of the physiological impact of mixed pollutants on physiology and feedbacks on emissions and the perspective of the vegetation acting as a filter for the removal of key pollutants and their reaction products, which in turn affects the oxidant balance of the mixed layer. In addition to the synergistic effects of some pollutants, the experiments indicated that ozone could affect subsequent hydrocarbon emissions; however, O_3 plus SO_2 seemed to have no measurable effect on emissions.

During the past year the BAC has continued to improve its ability to make stable isotope measurements. Using stable carbon isotopes and radiocarbon as investigative tools, they have characterized sites and biota that appear to be major sources of atmospheric methane and monitored the clean air site at Niwot Ridge. With an overall precision from sampling to measurement of ~0.10‰ for ^{13}C and ~1 pmC (percent modern carbon) for ^{14}C, they are using the most exacting experimental procedures possible to allow meaningful comparison between the various kinds of samples. They also began to measure D/H ratios in CH_4, an area for which very little data is currently available.

Their experimental research during this time period included continued monthly monitoring of ^{14}C and ^{13}C in atmospheric background methane at Niwot Ridge; continued collaboration with David Lowe and Martin Manning (both of INS) to compare results with Baring Head, New Zealand, collections; analysis of CH_4 and CO_2 in air samples from Canadian wetlands in a peat bog ecosystem (with Klinger and Zimmerman at NCAR and Tim Moore at McGill University, Montreal, Canada), studies of microbial uptake of CH_4 and the fractionation effect of bacteria on methane in temperate forested and tropical seasonal soils (with Crill, Keller, and Robert Stallard at the U.S. Geological Survey); studies of emissions of CH_4 and CO_2 from forested fens (with Crill); and a seasonal study of rice paddy methane with methane flux and isotopic measurements of carbon (with Katsu Minami and Kazuyuki Yagi of the National Institute of Agro-Environmental Sciences, Japan, and Ralph Cicerone at the University of California, Irvine).

Modeling efforts involving the methane budget are just beginning. Tyler and Lowe have begun some preliminary calculations and modeling of atmospheric methane budgets and source distributions using ^{13}C and ^{14}C isotope ratios with a two-box model developed by Manning. Tyler and Cicerone have made calculations concerning vertical gradients, reactions with sink processes, and other terms to describe the seasonal effects and general values for concentration and $\delta^{13}CH_4$ that are seen at Niwot Ridge.

During this time period, Edward Dlugokencky (unaffiliated visitor) left to join a research program at NOAA, Boulder. He was replaced by Brailsford (INS) who brings expertise in working with deuterium and tritium in atmospheric hydrogen and water. He has been integrated into all aspects of research in the isotope lab. Tyler and Brailsford continue to collaborate with Dlugokencky as he is involved in the NOAA monitoring station at Niwot Ridge.

Formaldehyde vapor is an important intermediate in the photochemical oxidation of methane and other hydrocarbons. During the first MLOPEX campaign, formaldehyde measurements made by an enzymatic technique developed in the BAC indicated significantly lower concentrations than theoretically expected. Further measurements by improved and/or independent techniques have high priority in subsequent MLOPEX studies. Wang Ying (visitor, Florida State University), Teresa Campos (ASP postdoctoral fellow), and Lazrus worked on ways to both improve the precision and reduce the detection limit of the technique to 30 pptv. A significant improvement was made by covalently bonding the enzyme to an immobilized substrate. Removal of background traces of formaldehyde in "pure" water used in the test by destructive photolysis has had promising initial results. This work is continuing in preparation for the next campaign.

Intercalibrations

One of the major emphases of the BAC section during 1990 was the development of procedures to insure that measurements can be referenced and compared with those of other colleagues. The BAC has formed a committee to initially examine the issues associated with relatively stable trace gases such as methane and nitrous oxide. The committee will expand to less stable gases and increase its membership to include non-NCAR participants during 1991.

A major effort of the BAC involving Heidt was to complete gas standard intercalibrations with Raymond Weiss (Scripps Institute for Oceanography), Timothy Bates and Kenneth Kelly (NOAA), and David Lowe (INS). Gases that were intercompared included methane, CO, N_2O, methyl halides, halons, and organo bromine compounds.

Tyler spent considerable time in 1990 spearheading the intercalibrations of isotopic standards and investigating effects of sampling procedures and processing procedures on the isotopic composition of methane. The laboratories participating include those of Lowe and Carl Brenninkmeijer (INS), Paul Quay (University of Washington), and Martin Wahlen, (Wadsworth Center for Laboratories and Research, Albany, New York).

The analysis of trace hydrocarbons in the atmosphere is complicated. Over 1,000 different hydrocarbon species may be emitted, and in continental air often more than 100 species can be seen. Intercomparisons of measurements are made more difficult because differences can occur due to incorrect component identification, incorrect calibrations, and problems in storage and handling. The international hydrocarbon intercomparison program began in 1990 to address these problems. The program, headed jointly by Calvert and Fehsenfeld (NOAA) and funded by NSF, EPA, NASA, and NOAA, will involve in its initial phase the circulation of hydrocarbon mixtures, certification of the contents, and tabulation of the results. Later phases will involve setting up logistics for intercomparisons made in the field. The BAC section will collaborate with a scientist to be hired to serve as a coordinator and independent analyst for the hydrocarbon intercomparison program. BAC scientists Zimmerman and Greenberg will provide initial training and instrumentation needed to begin the program.

In collaboration with William Sturges (CU) and Cornelius Sullivan (University of Southern California), Heidt and Pollock completed experiments in both polar regions to determine the biogenic production of bromine from ice microalgae. Using current estimates of bromine production rates, they have calculated that this algae source is competitive with global macroalgae production and with total anthropogenic production of all organic bromine gases.

As part of the joint Soviet-American Gas and Aerosol (SAGA-III) experiment, samples were collected from the research vessel *Korolev* for analysis of several different classes of organic compounds in the atmosphere over the equatorial Pacific Ocean (collaboration with Atlas and Anne Thompson, NASA). From these samples Pollock, Heidt, and Susan Schauffler (ASP postdoctoral fellow) were able to identify natural sources of methyl halides and bromine gases from surface waters in the equatorial Pacific.

Contributions to stratospheric chemistry from Heidt, Lueb, and Pollock consisted of further analyses of samples from the Airborne Arctic Stratospheric Expedition and data analysis and publications. Preparations have begun for the group's participation in the 1991–92 Arctic expedition.

Atmospheric Chemical Modeling Section

Modeling of Chemical Processes in the Troposphere

Madronich, in collaboration with student Christopher Rösselet (visitor, Paul Scherrer Institute, Geneva, Switzerland) and Laurel Sanford (visitor, University of Washington), completed version 3.0 of the NCAR "Master Mechanism," which recursively generates lists of chemical reactions necessary for simulation of the troposphere. A major component of this new version is a recursive computer code which generates the complete chemical photooxidation reaction sequences for any selected hydrocarbon, and further simplifies the reaction list based on user-specified precision. Madronich, together with Robert Chatfield, Calvert, Geert Moortgat (Max Planck Institute, Mainz, Germany), and Bernard Veyret and Robert Lesclaux (University of Bordeaux, France), completed simulations of the photochemistry from NASA's Amazon Boundary Layer Experiment (ABLE 2A) during the dry season. The results show that the observed levels of formic and acetic acids can be formed from complex gas phase interactions of secondary products of the photooxidation of hydrocarbons, mostly isoprene in this case. This is in contrast with a previous belief that these organic acids are primarily emitted by vegetation.

Modeling of the MLOPEX Observations

Madronich showed that theoretical values of the NO_x photostationary ratio are in good agreement with the values observed during the first MLOPEX. From this agreement, it can be inferred that the remote free troposphere near Hawaii is destroying ozone at a rate of about 0.5 ppb each day. The model results also show that a relatively small change in NO_x may effectively reverse this trend, leading to net ozone production. Model results for NO_2 photodissociation rates and for PAN and acetic acid production rates also appear to be in good agreement with the observations. Several discrepancies between the model and the observations were also identified (including HNO_3/NO_2 ratios and CH_2O concentrations), and will be one of the foci of the next scheduled MLOPEX campaign.

Improved Photodissociation Calculations

Madronich and Victor Filyushkin (Central Aerological Institute, Moscow, USSR) developed new radiation schemes for the calculation of molecular photodissociation rate coefficients in the troposphere and stratosphere. The new codes include comprehensive representation of pressure and temperature dependencies of scattering and absorption processes, improved wavelength and altitude averaging, and the latest available databases for solar irradiance and molecular absorption spectra. Significant changes in the calculated photodissociation rate coefficients have already been identified as a results of these refinements.

Three-Dimensional Chemical Transport Models of the Troposphere and Stratosphere

In order to study the behavior of trace species on the global scale in the troposphere and in the stratosphere, ACD scientists initiated the development of three-dimensional chemical transport models (CTMs). In cooperation with David Williamson and Philip Rasch (CGD), a detailed CTM is currently being developed by Brasseur and Stacy Walters. This model will be using dynamical parameters (wind and temperature fields, convective activity, etc.) provided by the latest version of the NCAR community climate model (CCM). Its horizontal resolution is 2.8 by 2.8 degrees. First tests of the transport code involved simulations of the behavior of long-lived species such as chlorofluorocarbons. The model was also used to simulate the dispersion of the effluents released from a fleet of high-altitude aircraft. While the transport code is currently being validated, a chemical scheme, which includes about 20 transported species and 25 equilibrium constituents, is under development. The model, which in the future will become available to the university community, will be a key component of NCAR's global tropospheric chemistry program. Brasseur and Müller also developed an intermediate model for the annual and global evolution of species (IMAGES). This model includes a detailed representation of the chemical sources and sinks of about 50 species including surface emissions, wet and dry deposition, and photochemical production and destruction, on a grid with $5° \times 5°$ resolution. The treatment of transport is based on monthly mean winds from the ECMWF climatology and specified eddy diffusivities. The model, which extends from the surface to the lower stratosphere with 24 levels in sigma coordinates, will be used to study the global budget of chemical compounds and describe the chemical environments in different regions of the world under different conditions.

Dynamics, Transport, and Chemistry of Trace Gases in the Middle Stratosphere

A parameterization of planetary wave breaking was developed by Rolando Garcia for use in conjunction with two-dimensional models of the middle atmosphere. The parameterization is an attempt to simulate the effect of nonlinear behavior associated with large-amplitude planetary waves while calculating explicitly the structure of only the largest-scale wave. It is based on the idea that nonlinearity arises from instability that occurs whenever the wave exceeds a certain amplitude criterion. In the well-known case of gravity waves, this criterion is the wave amplitude for which the lapse rate perturbation makes the total lapse rate convectively unstable. For planetary waves, the criterion is taken to be the amplitude for which the total potential vorticity gradient is reversed (thus fulfilling the classical condition for barotropic instability.) Thus, barotropic instability is assumed to be the mechanism that limits ("saturates") the amplitude of planetary waves. In practice, the parameterization is applied by calculating a dissipation rate that applies only in those regions where the breaking criterion is met. The dissipation rate estimated in this way is included in the dissipation term for the planetary wave equation at the following time step. Diffusion coefficients consistent with this dissipation rate can then be calculated from, for example, the linearized potential vorticity equation. Dissipation rates, diffusion coefficients, and the behavior of both the wave and the mean state calculated in this fashion are found to be in remarkably good agreement with observations, diagnostic determinations of diffusivity coefficients, and results from fully nonlinear numerical models. The parameterization was incorporated in the Garcia-Solomon two-dimensional model and will be used to study the behavior of chemical tracers in the stratosphere.

The Garcia-Solomon model was revised to obtain the behavior of the mean zonal wind directly from the momentum equation (instead of from the temperature field and geostrophic balance). With this revision, detailed studies of tropical circulations and their effects on chemical constituents should be possible. The mechanism of the semi-annual oscillation (SAO) is currently being investigated in collaboration with Fabrizio Sassi (visitor, University of L'Aquila, Italy). Although the two-dimensional model with a Kelvin wave parameterization is able to reproduce a credible oscillation in the zonal wind, the associated oscillation in meridional circulation is too weak compared to observations and cannot explain the double-peak structure observed in certain tracer fields such as methane and nitrous oxide. The reasons for this discrepancy are not understood at present; they are being investigated by diagnosing the momentum budget and mean meridional circulation of the NCAR CCM (stratosphere/mesosphere version), which apparently produces a more realistic SAO.

Sassi worked on the implementation of a finite-element numerical method for the solution of the advection equation for chemical constituents. He demonstrated the superior accuracy of the method compared to conventional finite differences, especially for tracer distributions that contain sharp spatial gradients. However, the method is computationally much more expensive than finite differences, thus restricting its application to situations (e.g., mesospheric NO) where the need to represent accurately the evolution of a tracer justifies the increased computational cost.

In collaboration with Susan Solomon (NOAA), the new version of the Garcia-Solomon model is being used to study the ozone depletion potential of hydrohalocarbons, in particular F-22. F-22 is destroyed slowly in the stratosphere and thus is expected to have a much smaller impact on stratospheric ozone than traditional chlorofluorocarbons such as F-11 and F-12. However, most studies of the ozone depletion potential of F-22 have been carried out using models that have upper boundaries at 50–60 km. This neglects the effects of transport into and out of the mesosphere, where F-22 can be destroyed more rapidly, and may lead to significant errors in the estimated ozone depletion potential in the high-latitude upper stratosphere. Although ozone decreases in this region will not dominate the behavior of the ozone *column*, the region is nevertheless of importance to early detection of ozone trends because local depletions are expected to be large.

Walters, Claire Granier (visitor, University of Paris, France) and Brasseur completed an improved version of their two-dimensional chemical-radiative-transport model. This new version, which is now used in several institutions in the United States and abroad, includes a parameterization of heterogeneous processes on polar stratospheric clouds and background stratospheric aerosols. Improvements introduced in the new version of the model include the treatment of multiple scattering, the parameterization of gravity wave breaking and Rossby wave absorption, an extension of the chemical and photochemical scheme, and substantial improvements in the numerical computational efficiency. The model was recently used to assess the importance of reactions on the surface of sulfuric acid aerosols and to determine how these reactions affect ozone during past volcanic periods. The potential perturbations to the ozone layer by chemical compounds (e.g., NO_x) released in the atmosphere by a proposed fleet of high altitude aircraft were also studied.

Granier and Brasseur used a three-dimensional mechanistic model of the stratosphere and mesosphere, based on the primitive equations and coupled to a rather detailed chemical scheme, to simulate polar vortex dynamics and ozone hole formation over Antarctica. Model simulations accurately reproduced winter and spring concentrations of key chemical species in the polar region. Differences between dynamical and chemical processes in the Antarctic and in the Arctic were highlighted.

Chemical Symbols

^{12}C, ^{13}C, ^{14}C	carbon 12, carbon 13, carbon 14
CFC	chlorofluorocarbon
CH_2O	formaldehyde
CH_3	methyl radical
CH_3F	fluoromethane
CH_3O	methoxy
CH_3O_2	methylperoxy
$CHClF_2$	Freon-22 (chloro difluoro methane)
CH_4	methane
$ClONO_2$	chlorine nitrate
CO	carbon monoxide
CO_2	carbon dioxide
COF_2	carbonyl fluoride
D	deuterium
F-11	trichloro fluoro methane ($CFCl_3$)
F-12	dichloro difluoro methane (CF_2Cl_2)
F-22	chloro difluoro methane (HCF_2Cl)
H	atomic hydrogen
H_2	hydrogen
H_2CO	formaldehyde
H_2O	water, water vapor
H_2O_2	hydrogen peroxide
H_2SO_4	sulfuric acid
HCl	hydrogen chloride (hydrochloric acid when in solution)
HF	hydrogen fluoride (hydrofluoric acid when in solution)
HNO_3	nitric acid
HO	hydroxyl radical
HONO	nitrous acid
HO_2	hydroperoxyl radical
j_{NO_2}	photodissociation rate coefficient for NO_2
j_{O_3}	photodissociation rate coefficient for O_3
N_2O	nitrous oxide
N_2O_5	dinitrogen pentoxide
NH_2	amidogen radical
NO	nitric oxide
NO_2	nitrogen dioxide
NO_3	nitrogen trioxide
NO_x	oxides of nitrogen
O, O_2	atomic oxygen, oxygen
O_3	ozone
OCS	carbonyl sulfide
OH	hydroxyl radical
PAN	peroxyacetyl nitrate
ROOH	organic hydroperoxide
RO_2	organic peroxyl radical
SF_2	sulfur difluoride
SF_6	sulfur hexafluoride
SO_2	sulfur dioxide

Staff and Visitors

Staff

Division Director's Office

Guy Brasseur (director)
Teresa Rivas (50%)
Donna Sanerib (50%)
Paul Sperry (50%)

Atmospheric Chemistry of Transient Species Section

Atmospheric Kinetics and Photochemistry Project
Jack Calvert (leader and section head)
Christopher Cantrell
Curtis Gilliland (long-term visitor)
Gregory Kok (50%)
Michael Mozurkewich (to 31 July 1990)
John Orlando
Richard Shetter
Geoffrey Tyndall

Atmospheric Odd Nitrogen Project
Elliot Atlas (long-term visitor)
Bruce Gandrud
Frank Grahek
John Lind (from 1 September 1990)
Brian Ridley (leader)
Thaddeus Sauvain (to 28 February 1990)
James Walega
Andrew Weinheimer

Global and Remote Observations Section

Global Observations and Modeling Project
Paul Bailey
Cheryl Craig
Eric Fetzer
John Gille (leader and section head)
Lawrence Lyjak
Steven Massie
Michael McGrath (long-term visitor)
Daniel Packman
William Randel (long-term visitor)
Charles Smythe

Optical Techniques Project
Michael Coffey
Alan Fried
Bruce Henry
William Mankin (leader)

Biosphere-Atmosphere Chemistry Section

In-Situ Measurements Project
Leroy Heidt (leader)
Richard Lueb
Walter Pollock

Biosphere-Atmosphere Interactions Project
James Greenberg
Alan Hills (from January 1990)
Elisabeth Holland
Stephen Shertz
Stanley Tyler
Patrick Zimmerman (leader and section head)

Plant-Atmosphere Gas Exchange Project
Christine Ennis
Allan Lazrus (leader)

Atmospheric Chemical Modeling Section

Robert Chatfield (to 23 May 1990)
Rolando Garcia
Sasha Madronich (acting head)
Stacy Walters

Visitor and Support Section

William Bradley
Edward Ellert
Timothy Fredrick
Bryan Lee (leader, Technical Element)
Teresa Rivas (leader, Clerical Element; 50%)
Donna Sanerib (50%)
Selena Slyter
Paul Sperry (leader, Administrators, and section head; 50%)
Marilena Stone
Sharon Vieyra

Affiliate Scientist

Aaron Goldman, University of Denver

Visitors

Mark Abrams; University of California, Berkeley; August 1990 to July 1991; Optical Techniques Project

Carol Beam; University of Colorado; February 1990 to August 1990; Director's Office

Bruce Bradshaw; University of Colorado; September 1990 to January 1991; Global Observations and Modeling Project

Gordon Brailsford; Institute of Nuclear Sciences, Lower Hutt, New Zealand; June 1990 to May 1991; Biosphere-Atmosphere Interactions Project

Monica Brisnehan; University of Colorado; May 1990 to August 1990; Atmospheric Odd Nitrogen Project

Tiffany Buckner; University of Colorado; September 1990 to May 1991; Biosphere-Atmosphere Interactions Project

Johanna Darlington; University of West Indies, Trinidad, West Indies; November 1989 to December 1989; Biosphere- Atmosphere Interactions Project

Edward Dlugokencky; Unaffiliated; July 1989 to July 1990; Biosphere-Atmosphere Interactions Project

David Edwards; Oxford University, England; August 1989 to August 1991; Global Observations and Modeling Project

Pierre Friedlingstein; Free University of Brussels, Belgium; June 1990 to September 1990; Atmospheric Chemical Modeling Section

Edward Gille; Yale University; May 1990 to August 1990; Atmospheric Chemical Modeling Section

Claire Granier; University of Paris, France; December 1988 to November 1990; Atmospheric Chemical Modeling Section

David Griffith; University of Wallongong, Australia; July 1989 to December 1989; Optical Techniques Project

Gary Hampton; Hampton Associates, Boulder; April 1990 to July 1990; Biosphere-Atmosphere Interactions Project

C. Nicholas Hewitt; University of Lancaster, England; June 1989 to October 1989; Plant-Atmosphere Gas Exchange Project

Alan Hills; University of Colorado; November 1989 to December 1989; Biosphere-Atmosphere Interactions Project

James Jaramillo; University of Colorado; April 1990 to August 1990; Director's Office

Tezz Johnson; University of Colorado; September 1989 to August 1990; Director's Office

Marisa Kadavonich; Metropolitan State University; June 1989 to August 1991; Biosphere-Atmosphere Interactions Project

Michael Keller; University of Wyoming; December 1989 to April 1990; Biosphere-Atmosphere Interactions Project

John Lind; Unaffiliated; February 1990 to August 1990; Atmospheric Kinetics and Photochemistry Project

Shaw Liu; National Oceanic and Atmospheric Administration, Boulder; May 1988 to December 1991; Director's Office

Edward Martell; October 1984 to September 1992; Director's Office

Didier Moreau; Belgium Institute for Space Aeronomy, Brussels; November 1989 to March 1990; Atmospheric Chemical Modeling Section

Jean-François Müller; Belgian Institute for Space Astronomy, Brussels; September 1989 to December 1989 and June 1990 to August 1990; Atmospheric Chemical Modeling Section

Cynthia Nevison; Stanford University; June 1990 to September 1990; Biosphere-Atmosphere Interactions Project

Karen Nickerson; Colorado College; May 1990 to August 1990; Atmospheric Kinetics and Photochemistry Project

Jerry Olson; Global Patterns Company, Lanoir City, Tennessee; September 1989 to August 1990; Biosphere-Atmosphere Interactions Project

Bryan Paul; Fairview High School, Boulder; September 1989 to December 1989; Plant-Atmosphere Gas Exchange Project

Mai Phan; University of Paris, France; April 1990 to May 1990; Atmospheric Chemical Modeling Section

Philippe Richaud; Bordeaux Observatory, France; February 1990 to March 1990; Atmospheric Chemical Modeling Section

Christopher Rösselet; Paul Scherrer Institute, Zurich, Switzerland; January 1990 to March 1990; Atmospheric Chemical Modeling Section

Peter Röth; Institute for Atmospheric Chemistry, Jülich, Germany; July 1990 to September 1990; Global Observations and Modeling Project

Tom Ryerson; University of Colorado; May 1990 to September 1990; Atmospheric Odd Nitrogen Project

Murry Salby; University of Colorado; August 1984 to December 1991; Atmospheric Chemical Modeling Section

Laurel Sanford; University of Washington; June 1990 to September 1990; Atmospheric Chemical Modeling Section

Fabrizio Sassi; University of l'Aquila, Italy; July 1990 to June 1991; Atmospheric Chemical Modeling Section

Thaddeus Sauvain; University of Colorado; September 1990 to May 1991; Atmospheric Odd Nitrogen Project

James Smith; University of Colorado; September 1987 to December 1990; Biosphere-Atmosphere Interactions Project

Susan Solomon; National Oceanic and Atmospheric Administration, Boulder; November 1983 to December 1991; Atmospheric Chemical Modeling Section

Frode Stordal, University of Oslo, Norway; June 1990 to August 1990; Atmospheric Chemical Modeling Section

John Taylor; Australian National University, Canberra; May 1990 to August 1990; Atmospheric Chemical Modeling Section

Margit Tritt; Metropolitan State College; March 1990 to May 1990; Biosphere-Atmosphere Interactions Project

David Valentine; Colorado State University; August 1990 to January 1991; Biosphere-Atmosphere Interactions Project

Claire Waelbroeck; Unaffiliated; October 1989 to December 1990; Atmospheric Chemical Modeling Section

Gillian Walford; University of Colorado; September 1989 to May 1990; Biosphere-Atmosphere Interactions Project

Curtis Westberg; Unaffiliated; September 1989 to August 1990; Biosphere-Atmosphere Interactions Project

Halvore Westberg; Washington State University; January 1990 to July 1990; Biosphere-Atmosphere Interactions Project

Beiying Wu; Academia Sinica, Beijing, People's Republic of China; January 1989 to August 1990; Global Observations and Modeling Project

Wang Ying; Florida State University; June 1988 to June 1990; Plant-Atmosphere Gas Exchange Project

Publications

Refereed Publications

*BLATHERWICK, R. D., *D. G. MURCRAY, *F. H. MURCRAY, *F. J. MURCRAY, A. GOLDMAN, *G. A. VANASSE, S. T. MASSIE, and R. J. CICERONE, 1989: Infrared emission measurements of morning stratospheric N_2O_5. *J. Geophys. Res. 94,* 18,337–18,340.

*BOTTENHEIM, J. W., *L. A. BARRIE, E. ATLAS, L. E. HEIDT, *H. NIKI, *R. A. RASMUSSEN, and *P. B. SHEPSON, 1990: Depletion of lower tropospheric ozone during Arctic spring: The Polar Sunrise Experiment 1988. *J. Geophys. Res. 95,* 18,555–18,568.

BRASSEUR G. P., C. GRAINIER, and S. WALTERS, 1990: Future changes in stratospheric ozone and the role of heterogeneous chemistry. *Nature 348,* 626–628.

——, *M. HITCHMAN, S. WALTERS, *M. DYMEK, *E. FALISE, and *M. PIRRE, 1990: An interactive chemical dynamical radiative two-dimensional model of the middle atmosphere. *J. Geophys. Res. 95,* 5639–5655.

CANTRELL, C. A., R. E. SHETTER, A. H. McDANIEL, and J. G. CALVERT, 1990: The rate coefficient for the reaction $NO_2 + NO_3 \rightarrow NO + NO_2 + O_2$ from 273 to 313 K. *J. Geophys. Res. 95,* 20,531–20,537.

——, J. DAVIDSON, A. McDANIEL, R. SHETTER, and J. CALVERT, 1990: Temperature-dependent formaldehyde cross sections in the near-ultraviolet spectral region. *J. Phys. Chem. 94,* 3902–3908.

*CARROLL, M. A., *D. R. HASTIE, B. A. RIDLEY, *M. O. RODGERS, *A. L. TORRES, *D. D. DAVIS, *J. D. BBRADSHAW, *S. T. SANDHOLM, *H. I. SCHIFF, *D. R. KARECKI, *G. W. HARRIS, *G. I. MACKAY, *G. L. GREGORY, *E. P. C, *M. TRAINER, *G. HUBLER, *D. D. MONTZKA, S. MADRONICH, *D. L. ALBRITTON, *H. B. SINGH, *S. M. BECK, *M. C. SHIPMAN, and *A. S. BACHMEIER, 1990: Aircraft measurements of NO_x over the eastern Pacific and continental United States and implications for ozone production. *J. Geophys. Res. 95,* 10,205–10,233.

*CHAMEIDES, W. L., *D. D. DAVIS, *J. BRADSHAW, *S. SANDHOLM, *M. RODGERS, *B. BAUM, B. RIDLEY S. MADRONICH, *M. A. CARROLL, *G. GREGORY, *H. I. SCHIFF, *D. R. HASTIE, *A. TORRES, and *E. CONDON, 1990: Observed and model-calculated NO_2/NO ratios in tropospheric air sampled during the NASA GTE/CITE-2 field study. *J. Geophys. Res. 95,* 10,235–10,247.

CHATFIELD, R. B., and A. C. DELANY, 1990: Convection links biomass burning to increased tropical ozone: However, models will tend to overpredict O_3. *J. Geophys. Res. 95,* 18,473–18,488.

——, and *P. J. CRUTZEN, 1990: Are there interactions of iodine and sulfur species in marine air photochemistry. *J. Geophys. Res. 95,* 22,319–22,341.

CICERONE, R., 1989: Analysis of sources and sinks of atmospheric nitrous oxide (N_2O). *J. Geophys. Res. 94,* 18,265–18,271.

DAVIDSON, J. A., C. A. CANTRELL, R. E. SHETTER, A. H. McDANIEL, and J. G. CALVERT, 1990: The NO_3 radical decomposition and NO_3 scavenging in the troposphere. *J. Geophys. Res. 95,* 13,963-13,969.

ENNIS, C. A., A. L. LAZRUS, P. R. ZIMMERMAN, and *R. K. MONSON, 1990: A branch chamber system and techniques for simultaneous pollutant exposure experiments and gaseous flux determinations. *Tellus 42B,* 170–182.

——, A. L. LAZRUS, P. R. ZIMMERMAN, and *R. K. MONSON, 1990: Flux determinations and physiological response in the exposure of red spruce to gaseous hydrogen peroxide, ozone, and sulfur dioxide. *Tellus 42B,* 183–199.

*FARMER, C. B., *B. CARLI, *A. BONETTI, *M. CARLOTTI, *B. M. DINELLI, *H. FAST, *N. LOUISNARD, *C. ALAMICHEL, W. MANKIN, M. COFFEY, I. *G. NOLT, *D. G. MURCRAY, A. GOLDMAN, *G. STOKES, *D. JOHNSON, *W. TRAUB, *K. CHANGE, *R. ZANDER, *L. DELBOUILLE, and *G. ROLAND, 1990: Balloon intercomparison campaigns: Results of remote sensing measurements of HCl. *J. Atmos. Chem. 10,* 237–272.

*FEHSENFELD, F. C., *J. W. DRUMMOND, *U. K. ROYCHOWDHURY, *P. J. GALVIN, *E. J. WILLIAMS, *M. P. BUHR, *D. D. PARRISH, *G. HÜBLER, *A. O. LANGFORD, J. G. CALVERT, B. A. RIDLEY, F. GRAHEK, B. G. HEIKES, G. L. KOK, J. D. SHETTER, J. G. WALEGA, *C. M. ELSWORTH, *R. B. NORTON, *D. W. FAHEY, *P. C. MURPHY, *C. HOVERMALE, *V. A. MOHNEN, *K. L. DEMERJIAN, *G. I. MACKAY, and H. I. *SCHIFF, 1990: Intercomparison of NO_2 measurement techniques. *J. Geophys. Res. 95,* 3579–3597.

FRIED, A., *J. R. DRUMMOND, B. HENRY, and J. FOX, 1990: Reduction of interference fringes in small multipass absorption cells by pressure modulation. *Applied Optics 29,* 900–902.

——, *L. NUNNERMACKER, *B. CADOFF, *R. SAMS, *N. YATES, *W. DORKO, *R. DICKERSON, and *E. WINSTEAD, 1990: Reference NO_2 calibration system for ground-based intercomparisons during NASA's GTE/CITE 2 mission. *J. Geophys. Res. 95,* 10,139–10,146.

GARCIA, R. R., and *R. T. CLANCY, 1990: Seasonal variation in equatorial mesospheric temperatures observed by SME. *J. Atmos. Sci. 47*, 1666-1673.

GILLE, J. C., 1990: Future observations of the middle atmosphere. In *Dynamics, Transport and Photochemistry in the Middle Atmosphere of the Southern Hemisphere,* (A. O'Neill, Ed.), Kluwer, Netherlands, 217–225.

GREENBERG, J. P., P. R. ZIMMERMAN, and P. HAAGENSON, 1990: Tropospheric hydrocarbon and CO profiles over the U. S. west coast and Alaska. *J. Geophys. Res. 95*, 14,015-14,026.

*GREGORY, G. L., *J. M. HOELL, JR., *A. L. TORRES, *M. A. CARROLL, B. A. RIDLEY, *M. O. RODGERS, *J. BRADSHAW, *S. SANDHOLM, and *D. D. DAVIS, 1990: An intercomparison of airborne nitric oxide measurements: A second opportunity. *J. Geophys. Res. 95,* 10,129–10,138.

——, *J. M. HOELL, JR., *M. A. CARROLL, B. A. RIDLEY, *D. D. DAVIS, *J. BRADSHAW, *M. O. RODGERS, *S. T. SANDHOLM, *H. I. SCHIFF, *D. R. HASTIE, *D. R. KARECKI, *G. I. MACKAY, *G. W. HARRIS, *A. L. TORRES, and A. FRIED, 1990: An intercomparison of airborne nitrogen dioxide instruments. *J. Geophys. Res. 95,* 10,103–10,127.

——, *J. M. HOELL, JR., B. A. RIDLEY, *H. B. SINGH, B. GANDRUD, *L. J. SALAS, and J. SHETTER, 1990: An intercomparison of airborne PAN measurements. *J. Geophys. Res. 95,* 10,077–10,087.

*HEWITT, C. N., G. L. KOK, and *R. FALL, 1990: Hydroperoxides in plants exposed to ozone mediate air pollution damage to alkene emitter. *Nature 344,* 56–58.

HILLS, A., and P. ZIMMERMAN, 1990: Isoprene measurement by ozone-induced chemiluminescence. *Analy. Chem. 62,* 1055–1060.

HOLLAND, E. A., and *J. K. DETLING, 1990: Plant response to herbivory and below ground nitrogen cycling. *Ecology 71,* 1040–1049.

*HUEBERT, B. J., *S. E. VANBRAMER, *P. J. LEBEL, *S. A. VAY, *A. L. TORRES, *H. I. SCHIFF, *D. HASTIE, *G. HUBLER, *J. D. BRADSHAW, *M. A. CARROLL, *D. D. DAVIS, B. A. RIDLEY, *M. O. RODGERS, *S. T. SANDHOLM, and *S. DORRIS, 1990: Measurements of the nitric acid to NO_x ratio in the troposphere. *J. Geophys. Res. 95,* 10,193–10,198.

*ISAKSEN, I. S. A., *B. ROGERUD, *F. STORDAL, M. T. COFFEY, and W. G. MANKIN, 1990: Studies of Arctic stratospheric ozone in a 2-D model including some effects of zonal asymmetries. *Geophys. Res. Lett. 17,* 557–560.

*KAYE, J. A., *A. R. DOUGLASS, *R. B. ROOD, *R. S. STOLARSKI, *P. A. NEWMAN, *D. J. ALLEN, *E. M. LARSON, M. T. COFFEY, W. G. MANKIN, and *G. C. TOON, 1990: Three dimensional simulations of hydrogen chloride and hydrogen fluoride during the airborne Arctic stratosphere expedition. *Geophys. Res. Lett. 17,* 529–532.

KOK G. L., A. J. SCHANOT, *P. F. LINDGREN, *P. K. DASGUPTA, *D. A. HEGG, *P. V. HOBBS, and *J. F. BOATMAN, 1990: An airborne test of three sulfur dioxide measurement techniques. *Atmos. Environ. 24A*, 1903-1990.

——, J. WALEGA, B. HEIKES, J. LIND, and A. LAZRUS, 1990: Measurements of hydrogen peroxide and formaldehyde in Glendora, California. *Aerosol. Sci. Tech. 12,* 49–55.

LI, S.-M., and J. W. WINCHESTER, 1989: Geochemistry of organic and inorganic ions of later winter Arctic aerosols. *Atmos. Environ. 23,* 2401–2415.

——, and J. W. WINCHESTER, 1990: Haze and other aerosol components in late winter Arctic Alaska, 1986. *J. Geophys. Res. 95,* 1797–1810.

——, and J. W. WINCHESTER, 1990: Particle size distribution and chemistry of late winter Arctic aerosols. *J. Geophys. Res. 95,* 13,897–13,908.

——, and J. W. WINCHESTER, 1989: Resolution of ionic components of late winter Arctic aerosols. *Atmos. Environ. 23,* 2387–2399.

——, J. W. WINCHESTER, *J. D. KAHL, *S. J. OLTMANS, *R. C. SCHNELL, and *P. J. SHERIDAN, 1990: Arctic boundary layer ozone variations associated with nitrate, bromine, and meteorology: A case study. *J. Geophys. Res. 95,* 22,433–22,440.

MADRONICH, S., and *G. WELLER, 1990: Numerical integration errors in calculated tropospheric photodissociation rate coefficients. *J. Atmos. Chem. 10,* 289–300.

——, and J. CALVERT,1990: Permutation reactions of organic peroxy radicals in the troposphere. *J. Geophys. Res. 95,* 5697–5715.

——, R. B. CHATFIELD, J. G. CALVERT, *G. K. MOORTGAT, *B. VEYRET, and *R. LESCLAUX, 1990: A Photochemical origin of acetic acid in the troposphere. *Geophys. Res. Lett. 17,* 2361–2364.

MANKIN, W. G., and M. T. COFFEY, 1989: Airborne observations of chemical constituents in the Antarctic winter stratosphere. In *Ozone in the Atmosphere,* Proceedings of the Quadrennial Ozone Symposium and Tropospheric Ozone Workshop, 1988, (R. D. Bojkov and P. Fabian, Eds.), Deepak Publishing, 22–25.

——, M. T. COFFEY, A. GOLDMAN, *M. R. SCHOEBERL, *L. R. LAIT, and *P. A. NEWMAN, 1990: Airborne measurements of stratospheric constituents over the Arctic in the winter of 1989. *Geophys. Res. Lett. 17,* 473–476.

——, M. T. COFFEY, *K. V. CHANCE, *W. A. TRAUB, *B. CARLI, *F. MENCARAGLIA, *S. PICCIOLI, *I. G. NOLT, *J. V. RADOSTITZ, *R. ZANDER, *G. ROLAND, *D. W. JOHNSON, *G. M. STOKES, *C. B. FARMER, and *R. K. SEALS, 1990: Intercomparison of measurements of stratospheric hydrogen fluoride. *J. Atmos. Chem. 10,* 219–236.

*PICKERING,K. E., *A. M. THOMPSON, *R. R. DICKERSON, *W. T. LUKE, *D. P. McNAMARA, J. P. GREENBERG, and P. R. ZIMMERMAN, 1990: Model calculations of tropospheric ozone production potential following observed convective events. *J. Geophys. Res. 95,* 14,049–14,062.

RANDEL, W. J., 1990: A comparison of the dynamic life cycles of tropospheric medium-scale waves and stratospheric planetary waves. In *Dynamics, Transport and Photochemistry in the Middle Atmosphere of the Southern Hemisphere,* (A. O'Neill, Ed.) Kluwer, Netherlands, 91–109.

——, 1990: Kelvin wave-induced trace constituent oscillations in the equatorial stratosphere. *J. Geophys. Res. 95,* 18,641–18,652.

——, and D. L. WILLIAMSON, 1990: A comparison of the climate simulated by the NCAR community climate Model (CCM1:R15) with ECMWF analyses. *J. Climate 3,* 608-633.

RIDLEY, B. A., and F. E. GRAHEK, 1990: A small, low flow, high sensitivity reaction vessel for NO chemiluminescence detectors. *J. Atmos. Ocean. Tech. 7,* 307–311.

——, J. D. SHETTER, B. W. GANDRUD, *L. J. SALAS, *H. B. SINGH, *M. A. CARROLL, *G. HÜBLER, *D. L. ALBRITTON, *D. R. HASTIE, *H. I. SCHIFF, *G. I. MACKAY, *D. R. KARECHI, *D. D. DAVIS, *J. D. BRADSHAW, *M. O. RODGERS, *S. T. SANDHOLM, *A. L. TORRES, *E. P. CONDON, *G. L. GREGORY, and *S. M. BECK, 1990: Ratios of peroxyacetyl nitrate to active nitrogen observed during aircraft flights over the eastern Pacific Oceans and continental United States. *J. Geophys. Res. 95,* 10,179–10,192.

——, J. D. SHETTER, J. G. WALEGA, S. MADRONICH, *C. M. ELSWORTH, F. E.

GRAHEK, *F. C. FEHSENFELD, *R. B. NORTON, *D. D. PARRISH, *G. HÜBLER, *M. BUHR, *E. J. WILLIAMS, *E. J. ALLWINE, and *H. H. WESTBERG,.1990: The behavior of some organic nitrates at Boulder and Niwot Ridge, Colorado. *J. Geophys. Res. 95,* 13,949-13,961.

*RINSLAND, C., A. GOLDMAN, *F. J. MURCRAY, *R. D. BLATHERWICK, *J. J. KOSTERS, *D. G. MURCRAY, *N. D. SZE, and S. T. MASSIE, 1990: Long-term trends in the concentrations of SF_6, $CHClF_2$, and COF_2 in the lower stratosphere from analysis of high-resolution infrared solar occultation spectra. *J. Geophys. Res. 95,* 16,477–16,490.

RODGERS, C. D., 1990: Characterization and error analysis of profiles retrieved from remote sounding measurements. *J. Geophys. Res. 95,* 5587–5595.

*ROSCOE, H. K., *B. J. KERRIDGE, *S. POLLITT, *N. LOUISNARD, *J. M. FLAUD, *J.-P. POMMEREAU, *T. OGAWA, *N. IWAGAMI, M. T. COFFEY, W. MANKIN, *W. F. J. EVANS, *C. T. McELROY, and *J. KERRY, 1990: Intercomparison of remote measurements of stratospheric NO and NO_2. *J. Atmos. Chem. 10,* 111–144.

*SALBY, M. L., *D. O'SULLIVAN, R. R. GARCIA, and *P. CALLAGHAN, 1990: Air motions accompanying the development of a planetary wave critical layer. *J. Atmos. Sci. 47,* 1179–1204.

——, R. R. GARCIA, *D. O'SULLIVAN, and *P. CALLAGHAN, 1990: The interaction of horizontal eddy transport and thermal drive in the stratosphere. *J. Atmos. Sci. 47,* 1647–1665.

——, and R. R. Garcia, 1990: Dynamical perturbations to the ozone layer. *Physics Today 43,* 38–46.

SASSI, F., *G. VISCONTI, and J. C. GILLE, 1990: Validation of parameterization scheme for eddy diffusion from satellite data. *J. Atmos. Sci. 47,* 2505–2515.

*SINGH, H. B., *E. CONDON, *J. VEDDER, *D. O'HARA B. A. RIDLEY, B. W. GANDRUD, J. D. SHETTER, *L. J. SALAS, *B. HUEBERT, *G. HÜBLER, *M. A. CARROLL, *D. L. ALBRITTON, *D. D. DAVIS, *J. D. BRADSHAW, *S. T. SANDHOLM, *M. O. RODGERS, *S. M. BECK, *G. L. GREGORY, and *P. J. LeBEL, 1990: Peroxyacetyl nitrate measurements during CITE 2: Atmospheric distribution and precursor relationships. *J. Geophys. Res. 95,* 10,163–10,178.

*SMITH, A. K., and G. P., BRASSEUR, 1990: The dependence of constituent transport on chemistry in a two-dimensional model of the middle atmosphere. *J. Geophys. Res. 95,* 13,749–13,764.

TURNIPSEED, A. A., *J. W. BIRKS, and J. G. CALVERT, 1990: Kinetics of the BrO + BrO reaction. *J. Phys. Chem. 94,* 7477–7482.

TYLER, S. C., D. C. LOWE, E. DLUGOKENCKY, P. R. ZIMMERMAN and R. J. CICERONE, 1990: Methane and carbon monoxide emissions from asphalt pavement: Measurements and estimates of their importance to global budgets. *J. Geophys. Res. 95,* 14,007-14,014.

WEINHEIMER, A. J., and B. A. RIDLEY, 1990: A cautionary note on the use of some mass flow controllers. *J. Geophys. Res. 95,* 9817–9821.

*WOFSY, S. C., *J. H. YATTEAU, *R. J. SALAWITCH, *M. B. McELROY, *G. C. TOON, W. G. MANKIN, and M. T. COFFEY, 1990: Heterogeneous conversion of COF_2 to HF in polar stratospheric clouds. *Geophys. Res. Lett. 17,* 461–464.

*YATTEAU, J. H., *S. C. WOFSY, *R. J. SALAWITCH, *M. B. McELROY, *M. R. SCHOEBERL, *L. R. LAIT, *P. A. NEWMAN, *A. TORRES, W. G. MANKIN, M. T. COFFEY, *G. C. TOON, *M. LOEWENSTEIN, *J. R. PODOLSKE, *S. E. STRAHAN, *K. R. CHAN, and *M. H. PROFFITT, 1990: Effects of atmospheric motions on nitrogen and chlorine compounds in the Arctic stratosphere. *Geophys. Res. Lett. 17,* 533–536.

* An asterisk denotes a non-NCAR author.

Climate and Global Dynamics Division

Overview

Our research program in the Climate and Global Dynamics (CGD) Division is directed toward understanding the physical basis of present and past climates and large-scale atmospheric and oceanic dynamics, thereby contributing to the basis for prediction of weather and climate. Over the last few years, our division priorities have been focused on many crucial issues of the global change program.

To accomplish these research objectives, we (1) expand and improve the community climate model (CCM); (2) use the CCM and other dynamical models to investigate the mechanisms of global climate changes and explore the scientific basis for long-range prediction of weather and climate; (3) investigate the limits of deterministic weather forecasting; (4) study the dynamics of global oceans and their interaction with the atmosphere; (5) analyze global observational data sets to study climate variability; (6) develop procedures to improve the treatment of clouds and their radiative properties in models and examine their effects on global energy balance using satellite observations; (7) develop satellite data as a resource in the global geosciences; (8) describe and model the interfaces between the atmosphere, oceans, cryosphere, chemosphere, and land-biosphere within the coupled climate systems concept; and (9) examine the role of human activity in inducing global environmental change and the response of society to such change.

In the past year, the planning and implementation of the Climate Systems Modeling Program (CSMP) has proceeded with substantial involvement of CGD, principally under Stephen Schneider's leadership. Several of our CGD scientists have helped in developing plans for increasing computer capacity in concert with UCAR and the Electric Power Research Institute. We expect that the CGD scientific program will continue to contribute to many of the scientific objectives of CSMP.

Division Organization

CGD is made up of seven sections or groups: the Climate Sensitivity and Carbon Dioxide Research Group (CSCORG), headed by Warren Washington; the Climate Modeling Section (CMS), headed by David Williamson; the Climate Analysis Section (CAS), headed by Kevin Trenberth; the Oceanography Section (OS), headed by William Holland; the Global Dynamics Section (GDS), headed by Akira Kasahara; the Environmental and Societal Impacts Group (ESIG), headed by Michael Glantz; and the Interdisciplinary Climate Systems (ICS) Section, headed by Schneider. The division office houses the director (Washington) and division administrative and computing systems staff.

Significant Accomplishments

- In continuing studies of the greenhouse effect, scientists discovered that the natural variability of regional patterns requires five- to ten-year averages in order for the warming signal to be evident. The ENSO events are also stronger in a warmer climate.

- Scientists, for the first time, have simulated the worldwide conveyor-belt circulation of temperature and salinity in a global ocean model.

- With a simplified three-dimensional stratospheric model, scientists simulated the quasi-biennial oscillation (QBO) of the equatorial lower stratosphere.

- Scientists sponsored the Third Workshop on the Community Climate Model, with participation of 70 scientists from universities, federal laboratories, and NCAR.

- Scientists completed comparison of spectral and semi-Lagrangian transport of water vapor in the CCM1 and identified deleterious interactions between errors attributable to the numerical approximations in the spectral approach and the physical parameterizations. No such interactions with the semi-Lagrangian approach were identified.

- In collaboration with the Climate Analysis Center at the National Meteorological Center (NMC), scientists produced a new sea surface temperature (SST) climatology in the form of an atlas with extensive documentation of the data.

- A scientist completed editing of the book, *Extratropical Cyclones: The Erik Palmén Memorial Volume* (available from the American Meteorological Society, or AMS).

- Scientists analyzed in detail the mean annual cycle of the surface wind stress over the global oceans and developed a new state-of-the-art climatology of global wind stress.

- Scientists analyzed band-pass-filtered data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to document the characteristics of storm tracks over the Southern Hemisphere (SH).

- Scientists found that diagnostic studies of the global mass, moisture, and heat budgets reveal shortcomings in the global ECMWF analyses and allow evaporation minus precipitation and diabatic heating to be computed as residuals. They are using the results to expand hypotheses on the origins of the 1988 North American drought.

- Using a statistical sampling theory and the CCM and ECMWF data, scientists determined error estimates in computing global mean temperatures due to imperfect spatial sampling.

- Scientists began a new initiative on global atmosphere–North Atlantic Ocean variability.

- Scientists began development of a surface ocean-ice model for future coupled studies of intradecadal variability.

- Scientists developed a very high resolution North Atlantic Ocean circulation model at $1/6°$ horizontal resolution to examine the role of eddies in the oceanic general circulation.

- Scientists completed a study of the generation, maintenance, and decay of 20- to 30-day waves that occur in the equatorial ocean and examined the sensitivity of these waves to various parameters.

- Scientists undertook studies of the nature of the North Atlantic conveyor-belt circulation (meridional overturning) to understand the strong heat fluxes into the high latitudes of the Northern Hemisphere (NH) and to examine the stability of this regime to various climatic perturbations.

- Scientists developed a new idealized coupled ocean-atmosphere model to study the dynamical mechanisms leading to the ENSO phenomenon. A successful 11-year test run exhibited many realistic features of interannual variability in the atmosphere-ocean system.

- Scientists identified two major energy sources for the recurring patterns of atmospheric low-frequency variability—transient eddy fluxes in the storm-track regions and interactions between the flow anomalies and the time-mean circulation.

- Scientists made significant progress in understanding one cause of the precipitation deficiency during the early stage of tropical forecasts. This will lead to a new approach to tropical data assimilation, particularly improving the analyses of horizontal divergence and moisture.

- Scientists hosted the Workshop on Numerical Long-Range Prediction of 10- to 90-Day Time-Mean Flows, with participation of 100 scientists and students from the university community, government laboratories, and operational forecasting centers.

- Scientists applied their refined forecasting-by-analogy method to a multinational and multidisciplinary project, using 15 historical analogies to ascertain the levels of resilience and vulnerability of fisheries to changes in abundance or variability of living marine resources.

- Scientists extended previous theoretical results on how the probability of occurrence of extreme meteorological events would be affected by changes in the average and variability of climate. The theoretical result—that the relative sensitivity of extreme events to the average or variability of climate is greater the more extreme the event—has been found to be quite robust.

- Scientists analyzed recent policy responses of water-provider organizations in the Denver metropolitan area to the veto by the Environmental Protection Agency (EPA) of a large dam and reservoir.

- Scientists have developed a core-contained version of CCM1 with expanded land-surface and sea-ice parameterizations.

- Daily variability diagnostics show that Asian monsoon simulation skill is highly dependent on surface-parameterization packages.

- Scientists have extended mesoscale embedding techniques to the Great Lakes region and Europe.

- Scientists have made the Biosphere-Atmosphere Transfer Scheme (BATS) operational on CCM1.

Climate Sensitivity and CO_2 Research Group

Carbon Dioxide Studies

Gerald Meehl and Washington documented changes in the climate basic state and carbon dioxide (CO_2) sensitivity in an atmospheric model coupled to a simple, nondynamic, slab-ocean, mixed-layer model with an altered snow and sea-ice albedo scheme. The revised albedo scheme produced differences in mean climate and increased sensitivity to CO_2. The differences are global and not confined to areas of snow and ice. The results indicate the importance of snow and ice to global climate and suggest that more realistic schemes should be used in future models to simulate more accurately these important processes.

Meehl, Grant Branstator, and Washington are studying the effects on ENSO of increased CO_2 in several model versions. Results indicate that ENSO continues to function in the tropics, but extratropical teleconnections associated with the alteration of atmospheric circulation from increased CO_2 are changed. In the tropics, absolute changes in precipitation and soil moisture indicate that dry areas would be drier and wet areas wetter in ENSO events with increased CO_2.

Meehl has continued his study of the simulation of ENSO in a global, coarse-grid, coupled, ocean-atmosphere general circulation model (GCM). Of particular interest are changes in ocean heat storage in one-year ENSO events compared to two-year events. This work has implications for alterations of ENSO with an increase of CO_2, since the upper-ocean heat budget is affected by both ENSO and increased CO_2.

Global Ocean Model Development and Application

Robert Chervin, in collaboration with Albert Semtner (NCAR affiliate scientist from the Naval Postgraduate School), completed a decadal integration of the parallel ocean climate model (POCM) with seasonal-cycle forcing and resolved eddies as an extension of an earlier multidecadal integration with annual mean forcing. Extensive analysis and diagnosis of POCM-archived data demonstrated that the three-dimensional flow fields of the model are quite similar to those observed (or thought to occur) in nature, especially considering the 1/2°, 20-level grid structure. For example, Chervin and Semtner found that deep western boundary undercurrents connected by the Antarctic Circumpolar Current complete the global thermohaline circulation, manifested by the surface flow through the Indonesian Archipelago and around the southern tip of Africa. The successful representation of the global conveyor-belt circulation may be the most important result of this model study. POCM has been converted to the UNICOS operating system, and a 1/4° version has been tested on the CRAY Y-MP8/864.

El Niño–Southern Oscillation Studies

Meehl, with Bruce Albrecht (Pennsylvania State University), analyzed the sensitivity of two versions of the CCM to ENSO SST anomalies in the tropical Pacific. One used standard convective adjustment and the other a hybrid convective scheme with mass-flux representation of heat and moisture, moist adiabatic adjustment representation of latent-heat release, and removal of moisture by precipitation processes. The model with the hybrid scheme was more sensitive to an ENSO SST anomaly than was the model with convective adjustment.

Significant improvements in the simulated teleconnection patterns associated with ENSO in the SH reflected the greatest improvements in the control simulation with the hybrid scheme in that hemisphere.

Meehl reexamined the mechanism of the semiannual oscillation at mid- and high latitudes in the SH. (Harry van Loon had first postulated the mechanism in the 1960s.) Meehl used more recent observed data and several GCM simulations to show that the annual cycle of SST and ocean heat storage near 50°S are important for the amplitude and phase of the semiannual oscillation. This has implications for the role of the semiannual oscillation in the initiation of ENSO events farther north in the tropics.

New Global Coupled Atmosphere, Ocean, and Sea-Ice Model

In the past year, Washington, Thomas Bettge, Lynda VerPlank, Gary Strand, and Meehl made significant progress on an improved coupled model system. They had already made test runs with a global 1°-horizontal-resolution, 20-layer version of the Semtner and Chervin ocean model, including the Arctic Ocean. This model yielded an ocean circulation similar to that of the Semtner-Chervin finer-resolution (1/2°), 20-level model, the major difference being the strength of the ocean eddies. The simulations have been vastly improved over the previous coarse-grid model with 5° horizontal resolution and 4 layers.

Other major components include the dynamic sea-ice model of Flato and Hibler programmed by David Pollard (unaffiliated visitor) and the three-layer thermodynamic sea-ice model of Semtner. These uncoupled models have been tested and are now being incorporated into a coupled climate system by Strand and Bettge. Because the models are multitasked, scientists will have the capacity on CRAY computers for efficient 100-year runs.

Scientists have configured the ocean and sea-ice portions of the model to be coupled either to a revised R15 CCM or to the new CCM2, soon to be available.

Regional Climate Change

To examine global and regional surface air temperature changes, Washington, Meehl, and VerPlank extended their experiments to nearly 70 years with their existing coupled atmosphere-ocean climate model. They calculated five-year seasonal means from year 26 to 50 to determine whether or not clear *regional* warming is evident for particular seasons. Five-year means are used rather than individual one-year seasonal means because the tropical Pacific El Niño and La Niña events produced by the coupled model can profoundly affect mid- and high-latitude regional patterns on the scale of individual years.

The new results suggest that, in order to observe the regional greenhouse effect signal, it may be necessary to consider changes in seasonal means only for periods substantially longer than five years. Changes over shorter periods may reflect natural variability much more than the transient greenhouse buildup. Future climate models with increased resolution and improved climate processes, such as clouds, will have to contend with the large natural variability of five-year or, perhaps, decadal time scales of regional patterns. This will make establishment of clear and consistent regional and seasonal greenhouse effects more difficult than previously believed. In addition, these results hint that identification of regional greenhouse effects in the observed data may also be more difficult to verify on a seasonal basis than annually. However, zonal mean temperature differences from all model averaging intervals show general warming in the troposphere and cooling in the stratosphere. Washington and Meehl, in collaboration with David Karoly (Monash University, Melbourne, Australia) are exploring this as a candidate for detection of a similar observed greenhouse climate change signal.

Climate Modeling Section

Research in the CMS encompasses a variety of modeling studies of the physical mechanisms governing the global climate system and the numerical techniques required to represent these mechanisms. CMS scientists also carry out observational studies, particularly in the comparison of models with observations. They are principally responsible for developing and testing new versions of the CCM and validating and using the CCM in the study of atmospheric circulation. They also study simpler models, such as two-dimensional shallow-water and zonally averaged chemical-dynamical models and one-dimensional column-radiation models. The CCM Core Group develops and maintains the standard versions of the CCM and its ancillary postprocessing code.

CCM2

All scientists in the CMS have been actively involved in the development and evaluation of the next CCM version (CCM2), to be available for general use at NCAR in October 1991. CMS staff brought the following major components to fruition this past year:

Planetary Boundary Layer. Byron Boville, in collaboration with Albertus Holtslag (Royal Netherlands Meteorological Institute, De Bilt), implemented a new boundary-layer parameterization in the CCM and tested it extensively. The scheme generally follows the formulation of Troen and Mahrt, although Boville and Holtslag have made significant revisions. In general, the behavior of the scheme is greatly improved over that of the simple stability-dependent diffusion used previously. Boville and Holtslag are investigating some pathological behaviors of the scheme under strongly nonequilibrium conditions.

Gravity-Wave Drag. Boville and Bruce Briegleb implemented a new gravity-wave drag scheme developed by Martin Miller (visitor, ECMWF, Reading, England). The new scheme incorporates different assumptions about the wave-breaking mechanisms that result in a significant change in the vertical profile of stress divergence. It also provides future utility for a nonisotropic formulation of the gravity-wave generation and deposition mechanisms. Initial tests suggest that the new scheme produces improvements in the jet structure that result primarily from the vertical redistribution of the gravity-wave drag.

Convective Parameterization. James Hack developed a stability-dependent treatment for moist convection for incorporation into the CCM2. His work follows the early research of Akio Arakawa and collaborators at University of California, Los Angeles, in which they utilize a three-level cloud model to adjust a moist adiabatically unstable atmospheric profile. The cloud-mass flux is determined by requiring that the convective activity result in a neutral stratification over some characteristic time scale. Hack uses the resulting mass-flux profile to estimate the convective-scale transport of an arbitrary set of passive scalars. The performance of this scheme in early prototypes of the CCM2 has been quite promising with significantly improved thermodynamic structures, particularly for moisture distribution in the tropics.

Cloud Parameterization. Hack and Jeffrey Kiehl formulated a new cloud algorithm for the CCM2, basing the cloud scheme, in part, on a scheme proposed by Julia Slingo (visitor, ECMWF). Changes in the cloud-prediction scheme include a dependence of high cloud on latitudinal tropopause structure and layered cloud dependence on local stability, in general. They also involve a cloud-fraction specification for nonprecipitating shallow clouds, along with changes to allow for marine stratus clouds associated with low-level inversions. Hack and Kiehl specified a cloud liquid-water concentration profile as a function of latitude and height, through a liquid-water scale height from which liquid-water pathlengths are calculated for use in the radiation parameterization. They compared simulations of cloud amount and the impact of clouds on the earth radiation budget to satellite data from the Earth Radiation Budget Experiment (ERBE) and the International Satellite Cloud Climatology Project (ISCCP).

Solar Radiation. Based on the delta-Eddington scattering approximation, Briegleb and Kiehl developed a new solar radiation scheme. With Anthony Slingo's cloud optical property parameterization, they created the delta-Eddington scheme and used available line-by-line calculations as a reference. Simple approximations handled partial cloud cover and overlap. The results showed excellent agreement with the line-by-line calculations. The new scheme is applicable from the surface to the midmesosphere and is much more general and flexible than the CCM1 solar scheme.

Transport Processes

Philip Rasch and Williamson completed a study demonstrating the sensitivity of the CCM1 model climate to the water vapor transport. They showed that the condensation parameterizations responded directly (and the clouds and radiative forcing indirectly) to the errors associated with the horizontal spectral and vertical finite-difference approximations in the CCM1, even at very high (T106) horizontal resolutions. They found no evidence of a computational error interacting spuriously with the physical parameterization when the shape-preserving semi-Lagrangian transport algorithms were used for water vapor. Elimination of this error component in the CCM1 resulted in a substantial change in the model climate. The new shape-preserving semi-Lagrangian transport of water vapor and an arbitrary number of additional constituents will be one component in the CCM2.

CMS scientists have distributed the basic semi-Lagrangian transport codes to several organizations for various uses, e.g., Battelle National Laboratory, Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Naval Oceanographic and Atmospheric Research Laboratory (NOARL), and NASA Marshall Space Flight Center. Rasch, with Erich Roeckner (Max Planck Institute for Meteorology, Hamburg, Germany), connected the transport modules to the Hamburg version of the ECMWF model and is investigating the sensitivity of climate to transport of water vapor and cloud water in this model. He expects to expand the study to other trace constituents in the future.

Code Development

The CCM Core Group (Linda Bath, Lawrence Buja, James Rosinski, and Gloria Williamson), led by Hack, made major changes to the CCM code in preparation for the CCM2. With the introduction of the CRAY Y-MP8/864 in fiscal year 1990 (FY 90), they adopted a large-memory implementation strategy to minimize the technical difficulties with multitasking both the semi-Lagrangian transport and spectral-transform algorithms. They completed major modifications to the prototype model in order to incorporate the semi-Lagrangian transport code into this new framework. They improved the flexibility to generate model history tapes, and they coded all physics parameterizations to meet the plug-compatible standards widely adopted by modeling centers.

Models Complementary to CCM

CMS scientists are developing several models complementary to the frozen tropospheric CCM. These models provide a somewhat simpler and less expensive framework than the complete CCM. They used these models, along with the prototype CCM2, for the following studies:

Mechanistic Model of the Stratosphere. Boville and Mariana Vertenstein developed a mechanistic version of the prototype CCM2 in which a specified geopotential distribution in the vicinity of 250 mb replaces the troposphere. This model is being used for studies of the internal dynamics of the stratosphere and can be run with varying degrees of sophistication in its treatment of radiation—from Newtonian cooling with specified (height-dependent) rate coefficients to full long-wave and solar calculations (with or without diurnal cycles).

Off-Line Transport Model. Williamson, Rasch, and Jerry Olson are developing an off-line version of the transport component of the CCM2. This model will include explicit large-scale advection by the shape-preserving semi-Lagrangian scheme and subgrid-scale planetary-boundary-layer (PBL) and convective transports. Either CCM output winds and state variables or analyzed atmospheric variables can drive the model, and it will be the basis for a community chemical transport model being developed in conjunction with the Atmospheric Chemistry Division (ACD).

Quasi-Biennial Oscillation

Masaaki Takahashi (Kyushu University, Fukuoka, Japan, and University of Washington) and Boville used the mechanistic version of the CCM to simulate the QBO. They demonstrated that the Holton and Lindzen theory of QBO does work in a fully three-dimensional model. They obtained their theoretical result by assuming the existence of two zonal waves, applying the Wentzel-Kramers-Brillouin approximation in the vertical, and integrating across the tropics to reduce the problem to one (vertical) dimension. Takahashi and Boville obtained QBO-like simulations by forcing the two waves directly at the lower boundary of the mechanistic model. They are examining the effect of the annual cycle on the simulations and the feasibility of simulating the QBO in the prototype CCM2.

Chemical Tracers in the CCM

With the prototype CCM2, Rasch and Guy Brasseur (ACD) began constructing and running scenarios of emission of a total odd nitrogen-like tracer in the upper troposphere and lower stratosphere by supersonic aircraft to understand the dynamics and chemistry of this region. They demonstrated a strong sensitivity in tracer distributions to the flight-corridor scenario, and the scenarios revealed a much stronger transport of tracer downward and equatorward than corresponding two-dimensional model-transformed Eulerian-mean transport circulations suggested.

Williamson, Rasch, and Brasseur, along with Dana Hartley and Ronald Prinn (both of the Massachusetts Institute of Technology, or MIT), experimented with scenarios of chlorofluorocarbon (CFC)-like tracers in the prototype CCM2 to understand tropospheric dynamics and chemistry and the role of the PBL and convective mass transports in trace-constituent distributions. They explored a variety of scenarios from simple idealized cases, such as that proposed for the World Climate Research Program (WCRP) Workshop on Long-Range Transport of Trace Gases, to realistic emission and loss processes. The former allows clean comparison between models, and the latter provides for additional validation of the transport capabilities of the CCM. The model shows reasonable accuracy in replicating the interhemispheric transport of CFC-11 and evidence of interesting episodic pollution events in both the tropics and midlatitudes, as observed in the atmosphere.

Equatorial Waves

In collaboration with William Randel (ACD), Boville has extensively analyzed the stratospheric equatorial waves simulated by the CCM and compared them to observations. They identified a new class of fast-mixed Rossby gravity waves in satellite observations after they were first identified in the model. Structures of equatorial waves generally are different from those of extratropical disturbances, and they have relatively long zonal wavelengths (greater than 10,000 km) and short vertical wavelengths (5–20 km). Their short vertical wavelengths make them difficult to capture in typical GCMs designed to simulate extratropical disturbances with vertical wavelengths greater than 10 km. Boville and Randel studied the dependence of the model's equatorial wave characteristics on the vertical resolution over a range of vertical grid spacings from about 700 to 2800 m. The equatorial wave solutions vary significantly over this range, with better results at finer resolution.

Trace Gases and Climate

Wei-Chyung Wang (State University of New York, Albany) and Kiehl developed and implemented a trace gas radiation model into the CCM1 and included the Covey-Thompson mixed-layer ocean model in this CCM1 version. They carried out a number of experiments—the model with no trace gas greenhouse effects, a simulation with current concentrations of trace gases, and a simulation with doubled CO_2 but no trace gases. Results indicate that, without trace gases, the globally averaged model surface temperature is too cold by 5 K, whereas with trace gases at present amounts the model-simulated surface temperature is in excellent agreement with observations (288 K). Comparison with the doubled CO_2 case indicates that the use of a pseudo-CO_2 amount to account for the radiative effects of the trace gases is not appropriate. Further simulations will include doubling CO_2 and increasing trace gases to future projected amounts.

Moist Processes

At the University of Stockholm, Sweden, Rasch worked with Hilding Sundqvist on the validation of a combined convective and stratiform cloud parameterization on a tropical data set from the Global Atmospheric Research Program's Atlantic Tropical Experiment study. The parameterization provides reasonable estimates of the moistening and heating rates and thus merits further examination. Work continues with focus on the evolution of cloud-water content distributions and the evolution of cirrus shields from the parameterization. While on collaborative leave at ECMWF, Rasch is developing a stratiform cloud parameterization and related parameterizations for turbulent diffusion and cloud fraction.

Rasch, with Peter Hess (ACD) and David Battisti (University of Wisconsin), completed a study in which they used a Kuo parameterization for deep convection (developed by Rasch) and a Manabe moist convective-adjustment parameterization to understand the interaction between SST, convection, and conditional instability of the second kind mechanisms in maintaining the intertropical convergence zone in an aquaplanet version of the CCM.

GCM Intercomparison

Kiehl, Hack, and Anthony Slingo continued to participated in the intercomparison of GCMs organized by Robert Cess (State University of New York, Stony Brook) and sponsored by the Department of Energy. A near-threefold variation exists in the climate-sensitivity parameter, as calculated by 19 different GCMs. The most recent work differentiated between the contributions to the climate-sensitivity factor of the long-wave and solar processes.

Radiation Model Comparison

Kiehl and Briegleb, with Daniel Schwarzkopf (Geophysical Fluid Dynamics Laboratory, or GFDL) and Andrew Lacis (Goddard Institute for Space Studies, or GISS), completed a detailed analysis of the performance of the radiation models employed in all versions of operational GCMs at NCAR, GFDL, and GISS. They determined that the latest model versions at these centers are in fairly good agreement with line-by-line calculations, but they sorely need more information on the water vapor continuum to improve further the radiative cooling rates in the lower troposphere.

Numerical Aspects

Rasch and Piotr Smolarkiewicz (Mesoscale and Microscale Meteorology Division, or MMM) developed a theoretical formalism that allows any Eulerian transport method to be used in a semi-Lagrangian framework. This removes the

Courant-number constraint that is so restrictive in spherical geometry and allows many numerical methods that could not be considered before to be used on the sphere.

During his collaborative leave at ECMWF, Williamson began study of the truncation error in spectral models associated with the sigma vertical coordinate system. In idealized systems, he showed how vertical temperature inversions near mountains can lead to large errors in the horizontal pressure gradient and spurious convergence. This error is particularly large in the first few layers above the surface and can only be reduced by smoothing the mountains with respect to the spectral resolution. The CCM1 produces spurious precipitation over certain mountain ranges. Because this spurious precipitation and the time-average model-simulated pressure gradient look suspiciously like they are related to the error identified by Williamson, he is pursuing this connection.

Williamson and Hack joined Paul Swarztrauber and Richard Sato (Scientific Computing Division, or SCD) and members of ANL and ORNL under the Computer Hardware, Advanced Mathematics, and Model Physics initiative, to study the implementation of the CCM2 on massively parallel computers. Initially, they are analyzing the suitability of current state-of-the-art algorithms and methods for advanced computer architecture. With Rüdiger Jakob (visitor, University of Colorado), they are developing global, spectral-transform, shallow-water and semi-Lagrangian codes to isolate the implementation issues associated with those algorithms. Once they develop efficient implementations for these algorithms, they will install the CCM2 on several massively parallel computers. SCD's section of this report provides further details of this project.

The current renewed interest in alternative numerical methods for global models is due to a variety of reasons. The computational cost of the Legendre transform associated with the spectral method will become a significant fraction of the total cost of models at high resolutions and, thus, other methods are likely to become economically competitive. The spectral representation contributes to unphysical structures in the predicted fields, such as negative water vapor. Recently developed shape-preserving and essentially nonoscillatory schemes have addressed this issue. Over steep mountains, the horizontal pressure gradient force in the sigma system is a small difference of two large terms and difficult to approximate accurately. Mesh refinement near mountains or admittance of explicit lateral boundaries where mountains can penetrate the grid are potential alternatives.

Because of the renewed interest in algorithm development, Williamson, John Drake (ORNL), Hack, Jakob, and Swarztrauber defined a set of standard test cases with which potential schemes may be compared in a shallow-water model framework. This standard test set should encourage the continued exploration of alternative numerical methods and provide the community with a mechanism for judging the merits of numerical schemes and parallel computers for atmospheric flow calculations.

CCM Workshop

NCAR was the site of the third CCM workshop for two weeks in July 1990. Nineteen students attended sessions the first week, which consisted of tutorials and hands-on experience in running and changing the model and processor. Over 70 scientists (including representatives of all sections of CGD) participated in the second week of scientific presentations and discussions. Members of the CCM Core Group provided critical technical and educational support.

CCM Core Group

The introduction of the CRAY Y-MP brought with it a major operating system change, requiring conversion of both the CCM1 and the CCM modular processor. Scientists and programmers carried out the CCM conversion over a period of several months, during which time they discovered many problems with the input/output and mass storage components of the system which were subsequently corrected by SCD. The conversion of the CCM processor was a more serious problem since Richard Wolski, its principal architect, had died in early January. Consequently, Thomas Mayer, over a six-month period, carried out the conversion, which involved incorporation of Graphical Kernel System graphics and major modifications to the file-handling capabilities. Buja has since joined the CCM Core Group and assumed responsibility for maintaining the processor.

Climate Analysis Section

The research goal of the CAS is to improve understanding of the atmosphere primarily through empirical studies and diagnostic analyses of the atmosphere and its interactions with the earth's surface and oceans on a wide range of time scales. Focus is on atmospheric general circulation and meteorological phenomena and climate variations over several time scales, such as those involved in blocking events; 40- to 50-day tropical oscillations; interannual variations, such as the ENSO phenomenon; the 1988 North American drought; solar-weather relationships; and longer-period trends.

In the CAS, a central ongoing thrust relates to data sets and includes acquisition of data, evaluation, improvement and restructuring of data sets, development of climatologies, and the use of the data sets in diagnostic studies. CAS scientists are also pursuing several theoretical and modeling studies. The research spans many topics and includes several studies that are part of national and international programs—Tropical Oceans and Global Atmosphere (TOGA), ERBE, ISCCP, and global change. CAS scientists interacted with other CGD sections—GDS on planetary-wave modeling; ICS and CMS on analysis of CCM data, validation of the CCM and planning future experiments; and OS on problems involving atmospheric-ocean coupling of mutual interest, such as TOGA.

Data Sets

CAS scientists, and Dennis Shea, Amy Solomon, and Jeffery Berry in particular, continued collaboration with SCD's Data Support Section to acquire and validate data. Ongoing efforts were aimed at conventional meteorological data and analyses, but model and satellite data were increasingly included as well. Laura Smith (visitor, Colorado State University) analyzed ERBE and ISCCP data. Shea, along with Trenberth and Richard Reynolds (NMC), produced a new SST climatology in atlas form, as well as a time series from 1982 onward in a form suitable for use with the CCM. The climatology document is available in computer-compatible form from the Data Support Section.

Trenberth and Solomon continued to evaluate global analyses from ECMWF and NMC for 1979–90. They updated ECMWF data from the World Meteorological Organization (WMO) archive (twice daily, seven levels) through 1989 in CCM history-tape format at T42 and R15 resolutions and prepared a special two- to eight-day band-pass-filtered data set at T42 resolution updated through 1989. Berry and Solomon acquired and are processing the new ECMWF/WCRP global analyses (T106 resolution, four times per day, 14 levels in the vertical) into forms suitable for the CCM processor at different truncations. Trenberth, Solomon, and Shea, in collaboration with John Christy (University of Alabama, Huntsville), analyzed some aspects of the Comprehensive Ocean-Atmosphere Data Set (COADS) and performed intercomparisons between surface-data temperature fields and channel-2 microwave-sounder-unit data from satellite on tropospheric temperatures.

General Circulation

Chester Newton, along with coeditor Eero Holopainen (University of Helsinki, Finland), completed editing of the AMS book, *Extratropical Cyclones: The Erik Palmén Memorial Volume.*

Harald Lejenäs (University of Stockholm, Sweden) and Roland Madden related the 16-day wave—a zonal wave number one westward-propagating Rossby mode—to incidences of blocking. Using techniques developed by Madden and Peter Speth (University of Cologne, Germany) to isolate the traveling wave and those developed by Lejenäs and Hans Okland (University of Oslo, Norway) to identify periods of blocking, Lejenäs and Madden showed that the beginning and retrogression of many blocking episodes are coincident with the passage of the ridge of the 16-day wave.

Using eight years of ECMWF analyses, Madden, Speth, and Speth's student, Wilhelm May, extended earlier observational studies of large-scale traveling waves. The new emphasis is on SH data, and they are doing the work with a minimum of space and time filtering so that the structures and time scales determined will not be influenced by the analyses.

Madden and David Gutzler (Atmospheric and Environmental Research, Inc.) have begun a study of the seasonal changes in atmospheric angular momentum (AAM) in its local variability and spatial covariability. Initial results indicate that fluctuations in the total AAM are dominated by those in the tropics. There are maxima in the daily variability of AAM in the solstice seasons, with the largest in northern winter. Because tropical variability often exceeds total variability, the tropical and extratropical AAM must vary out of phase.

Julia Slingo and Madden completed their study of a tropical intraseasonal oscillation present in CCM simulations. Its structure is similar to that of the observed 40- to 50-day oscillation; however, in common with other model simulations, its period (near 25 days) is shorter than observed.

Shoichi Taguchi (visitor, National Research Institute for Pollution and Resources, Ibaraki, Japan) has also analyzed the ECMWF data, both total and band-passed fields, in order to illuminate the evolution of storms and interactions with the zonal mean flow.

Using ECMWF data, Trenberth, Olson, and William Large comprehensively analyzed surface wind stress over the global oceans. They analyzed the mean annual cycle in detail and compared results with previous climatologies. Some differences over the NH are real manifestations of climate change. Over the southern oceans, the new wind-stress values are believed to be the most reliable values available and much larger than in previous climatologies.

Trenberth and Olson examined nine years of ECMWF analyses to assess how well a sparse 63-station network might depict climate changes. Although correlations between 128×64 grid data and the 63-station subset over large zones are quite high, the 63-station network has larger amplitudes outside the tropics and is vulnerable to missing data.

Trenberth and Solomon developed general diagnostic-analysis programs to (1) analyze in detail the mass budget in the atmosphere, including computing evaporation minus precipitation as a residual of the moisture budget; and (2) compute diabatic heating as a residual from the thermodynamic equation. Mass is not well conserved in the ECMWF analyses, either locally in three dimensions or when vertically integrated. Trenberth and Solomon drew implications on the way the analyses should be used and the need to validate the results from the moisture and heat budgets. They also computed orographic forcing and concluded that it is too small in the ECMWF model used in the four-dimensional data assimilation.

Focusing on the SH, Trenberth has used the band-pass-filtered global analysis from ECMWF to highlight two- to eight-day fluctuations to illuminate relationships among variables in baroclinic storm-track regions. Locations of the jet stream and variance maxima of geopotential height, wind components, temperature, moisture, vorticity, divergence, and vertical motion bear a distinct relationship to the storm track and so, too, do many flux quantities. The relationships can generally be understood in terms of geostrophic theory and perturbation analysis applied to baroclinic systems.

El Niño–Southern Oscillation and the 1988 North American Drought

Trenberth reviewed the general characteristics of ENSO for a book chapter, focusing on atmospheric processes and coupling with the tropical oceans, especially the link between warm water and convergence zones, in both the mean annual cycle and interannual variations.

Trenberth, with Branstator, continued work on the origins of the 1988 North American drought—how it developed and possible causes. The observational evidence of a strong wavetrain across North America in the spring and summer, which provided large-scale support for the drought, indicated the probable importance of the Pacific Ocean, where tropical SST anomalies had reversed from warm 1987 El Niño conditions to very cold (La Niña) conditions by April. Trenberth and Solomon contrasted the diagnosed diabatic heating in the tropics during May 1988 (the time of the drought) with May 1987 (during El Niño). Differences qualitatively agreed with changes in outgoing long-wave radiation, as seen from satellite, and were consistent with the changes in SST and changes in atmospheric forcing to produce the anomalous wavetrain responsible for the drought. Planetary-wave modeling of possible forcings indicated that the dry conditions across North America and the role of land-surface processes in the drought were secondary but constituted an important feedback process.

Van Loon is working with George Kiladis and Klaus Weickmann (University of Colorado) on case studies of onsets and demises of extremes in the Southern Oscillation.

Van Loon began work with Tsing-Chang Chen (visitor, Iowa State University) on mechanisms of shorter-term climate changes.

Solar-Weather Relationships

Van Loon and Karin Labitzke (NCAR affiliate scientist from the Free University of Berlin, Germany) are studying what appears to be a probable effect of the 11-year solar cycle on low-frequency variability in the atmosphere. They are focusing on the warmer part of the year (April-October) when it is not necessary to filter the data through the QBO to obtain a large signal. In these months, the effect of the 10- to 12-year oscillation is especially strong between 8 and 25 km. The short sample (40 years) and the lack of an explanation of the 10- to 12-year oscillation are still limiting the conclusions to be drawn from the study.

Climate Change

Using data from a CCM simulation (Branstator), ECMWF analyses (Trenberth, Solomon, and Olson), COADS, and the World Monthly Surface Station Climatology (Shea), Madden examined the error in estimating global mean temperatures due to imperfect spatial sampling. His preliminary results indicate that this error ranges from just under 0.20°C (0.25°C) before 1900 to approximately 0.07°C (0.10°C) after 1950 for annual (January) averages.

As part of his activities with the scientific assessment of climate change for the Intergovernmental Panel on Climate Change and for the Board on Atmospheric Sciences and Climate of the National Academy of Sciences (NAS), Trenberth reviewed atmospheric circulation changes and relationships with surface temperature and precipitation throughout this century and in both hemispheres. Another aspect of this is emphasized in a separate review of NH and SH contrasts in the earth system response to global change, with emphasis on the physical processes of importance in climate change on decadal time scales. For the NAS Water Resources Board, he further surveyed future issues of importance with respect to climate change and water resources in the West.

Trenberth analyzed large-scale observed trends in the circulation over the extratropics of the NH and found large changes in the North Pacific from 1977 to 1988. These corresponded to a significantly deeper-than-normal Aleutian low-pressure system in the winter from November through March. The largest surface warming anywhere in the hemisphere has been in Alaska and along the west coast of North America, and it results from increased southerly flow bringing warmer and moister air into the region. Colder-than-normal sea temperatures in the North Pacific are also a consequence of the circulation change and reveal large spatial structure in the temperature changes. The 1977–88 regime is believed to be linked to events in the tropics and the three El Niño events during that interval, but to no corresponding cold events.

Oceanography Section

OS scientists focused on (1) developing an understanding of large-scale ocean circulation through studies of the important processes in the global ocean, and (2) examining the relationship of these processes to the dynamics of climate through studies of the key air and sea interactions occurring at the interface between the two. This work involved studies in ocean circulation modeling, theory, and observations, and air-sea interaction. As in past years, the emphasis was on numerical modeling of basin- and regional-scale ocean circulation in both equatorial and midlatitude regimes, development of global models, idealized process studies in geophysical fluid dynamics, and analysis and interpretation of observational data.

New Initiatives

OS scientists began two new initiatives in FY 90. The first, led by Large and James McWilliams, was the development of a numerical model of the upper ocean and sea ice for intradecadal climate studies. This model is intended for coupling to atmospheric GCMs in order to investigate the interaction of atmosphere and ocean and to identify possible sources of climate drift in coupled models. It is also intended for biological and chemical coupling, although initially this is not the primary thrust. The upper-ocean model includes the advection and mixing of temperature and salinity in the presence of a velocity field diagnostically determined from a linear momentum balance (pressure-gradient and Coriolis forces and vertical mixing by small-scale motions). Upper boundary conditions are the air-sea or ice-sea fluxes. Lower boundary conditions are the time-mean general circulation plus the steady-state response to the current wind forcing in the equatorial zone. A significant part of the effort will be the assemblage and comparison of observed surface and upper-ocean quantities with model solutions. The major innovation will be to apply vertical mixing theories and parameterizations developed for the turbulent atmospheric PBL to the upper ocean. Sea ice will be included in the model through collaboration with W. Brechner Owens (Woods Hole Oceanographic Institution, or WHOI).

The second new initiative, carried out by Holland, Frank Bryan, and Julianna Chow, involves the use of a North Atlantic basin model to unravel the basic balances governing the conveyor-belt (meridional overturning) circulation associated with today's climate regime. The aims of this study are to understand the reasons for the present strong heat fluxes into the NH in the Atlantic Ocean sector and to examine the stability of this system. In particular, Holland, Bryan, and Chow are looking at the role of local and distant thermohaline forcing as well as the contribution of present-day wind stress forcing. They are examining the potential for a thermohaline catastrophe caused by CO_2 or other human- and/or nature-induced variations in oceanic surface-boundary conditions.

Modeling of Midlatitude Ocean Circulation

The small-scale physical processes involved in convective overturning in the ocean must be parameterized in large-scale models. The traditional approach to this parameterization has been to apply an adjustment to the solution at each time step that attempts to remove regions of static instability generated by the other processes operating in the model. An alternative approach is to make the coefficient of vertical diffusion several orders of magnitude larger than its value in statically stable conditions wherever an unstable region is detected. Unfortunately, neither the conventional implementation of the adjustment scheme nor the enhanced diffusion scheme actually restores static stability in the solution. Bryan developed a new implementation of convective adjustment that guarantees a statically stable solution within a finite number of iterations. He is investigating the sensitivity of the large-scale circulation to the choice of parameterization of convection through a series of experiments in an idealized sector-ocean GCM.

Peter Gent, McWilliams, Dale Haidvogel (NCAR affiliate scientist from Johns Hopkins University), Ralph Milliff (visitor, UCAR), and Eric Chassignet (Advanced Studies Program, or ASP, postdoctoral fellow) continued studies of the balanced dynamics of the oceanic general circulation. In particular, they examined a dynamical hierarchy for wind-driven adiabatic circulation in baroclinic and single-layer cases. They studied control of boundary-current separation by lateral-stress boundary conditions for partial-slip, free-slip, and no-slip boundary conditions and developed subgrid-scale parameterization formulas for diabatic circulation. These formulas transport material properties along isopycnals but have diapycnal transports based upon geostrophic-adjustment turbulent mixing controlled by the Richardson number.

Holland and Bryan carried out further experiments in the World Ocean Circulation Experiment (WOCE) community modeling effort (CME) at 1/3° resolution. They started a new very high resolution CME run at 1/6° horizontal resolution for comparison with 1/3° results. The new model shows much improved development of the eddy field and substantial changes in the large-scale circulation.

Bryan continued development of ocean circulation models suitable for ocean chemistry and biology research. His major activities were the configuration, testing, and tuning of a CME version of the North Atlantic model with additional vertical resolution in the photic zone (0–200 m). This model will be used with an ocean ecosystem model developed by Jorge Sarmiento (Princeton University) to study the distribution and variability of primary production in the ocean. Bryan is tuning the model circulation and mixing processes to provide as realistic as possible a simulation of the vertical exchange processes in the upper ocean. These processes are crucial in determining the supply of nutrients to the photic zone and, hence, the primary productivity of the ocean. The eventual goals of this line of work are to estimate the rate of total carbon uptake by the ocean and to examine how the processes involved might change in different climate scenarios.

Holland, Antonietta Capotondi (ASP graduate research assistant), Chassignet, and William Schmitz (WHOI) continue to use regional models of the Gulf Stream to examine high-resolution meander processes. In some experiments, they are using data assimilation with the Navy's ocean satellite altimeter (GEOSAT) to simulate realistic behavior in the Gulf Stream system. They are studying sophisticated optimal interpolation techniques and data assimilation into the Gulf Stream model.

Holland and John Schultz (ASP graduate research assistant) began development of a regional primitive-equation model of the East China Sea, including its interaction with the open ocean western Pacific. This work is being carried out in conjunction with an observational program for that region by Philip Hsueh (Florida State University). Studies of the role of Kuroshio meandering and eddy shedding in transporting heat and water mass between the East China Sea and the open Pacific are under way.

Equatorial Circulation

Gent and Mark Cane (Lamont–Doherty Geological Observatory) continued to collaborate on their primitive-equation model of the upper equatorial ocean. They developed the model to accommodate realistic horizontal geometry and performed a seasonal-cycle calculation for the tropical Pacific. They are comparing calculated SSTs to observations and will tune the heat-flux parameterization based upon this comparison. The resulting calculated values of the heat flux for the ocean model will probably be better than the notoriously poor climatologies from observations.

Gent and Jeffrey Proehl (ASP postdoctoral fellow) have nearly completed a study of the generation, maintenance, and decay of 20- to 30-day waves in the equatorial ocean model. They have calculated the sensitivity of these waves to wind forcing, ocean stratification, friction, and other parameters. This work is a modeling contribution to the Tropical Instability Wave Experiment.

Studies in Geophysical Fluid Dynamics

McWilliams and various collaborators accomplished a large number of idealized studies of geophysical fluid processes. An important process for the general circulation is the form of stress exerted on large-scale flow by local flow around topography. This has been investigated in a channel geometry with Anne Marie Treguier (formerly with ASP) as an idealization of the Antarctic Circumpolar Current. Another general circulation process is global-scale thermohaline convection. With Olivier Thual (ASP postdoctoral fellow), OS scientists analyzed its configuration of possible steady states—or catastrophe structure—in a two-dimensional fluid model and found the results to be quite similar to the steady states for low-order box models.

Several problems of mesoscale dynamics were also solved. With Emile Hopfinger and Jacques Verron (both of the Institute of Mechanics, Grenoble, France), McWilliams found that the important process of baroclinic vortex merger has a significant sensitivity to the initial vortex shapes, and this attribute reconciles previously contradictory claims in the literature. With Richard Mied (Naval Research Laboratory) and through the geostrophic or balanced adjustment of a localized momentum pulse in the presence of a preexisting tracer gradient, McWilliams simulated the mushroom-like patterns on the sea surface that are frequently observed from imaging satellites. With Pascale Lelong (ASP postdoctoral fellow), he solved the counterpart of this problem in a nonrotating stably stratified fluid (i.e., cyclostrophic adjustment). McWilliams, with Sue Haupt (ASP postdoctoral fellow and visitor) and Joseph Tribbia, found solutions for the stationary dipolar states (i.e., modons) in a mean horizontal shear flow. Studies are under way with Milliff and Vitaly Larichev (visitor, Shirshov Institute of Oceanology, Moscow, USSR) of the adjustment of coastal sea level through gravity and Kelvin-wave radiation to the later-time quasi-geostrophic state of approximate uniformity along the coast. As a companion to this latter study, some tests of multigrid numerical techniques for implicit time integration of the shallow-water equations have begun with Achi Brandt (Weizmann Institute, Rehovot, Israel) and John Ruge (University of Colorado).

McWilliams also investigated the fundamental processes of geostrophic turbulence. With the dynamics of coherent vortices in anisotropic turbulence a primary focus, he developed an automated vortex census analysis and applied it to two-dimensional and geostrophic turbulence; demonstrated their control of the cascade and dissipation rates in two-dimensional turbulence; with Larichev, demonstrated their occurrence for turbulence in the shallow-water equations on scales much larger than the deformation radius; and, with Larichev and Alexander Fedotov (visitor, Shirshov Institute of Oceanology, Moscow, USSR), demonstrated dipole coherence when particle and Rossby wave speeds are comparable. In collaboration with Jeffrey Weiss (ASP postdoctoral fellow), George Carnevale and William Young (Scripps Institution of Oceanography, or SIO), and Yves Pomeau (Ecole Normal Supérieure, Paris, France), McWilliams proposed a scaling theory for two-dimensional turbulence and modeled it with a simple model of Hamiltonian point-vortex dynamics, punctuated by nonconservative merger events. He and Michael Spall (WHOI) demonstrated that turbulence in the shallow-water equations satisfies nonlinear balanced dynamical relations quite well across a broad range of environmental rotation and stable stratification and that the interaction between balanced motions and gravity waves is weak and consistent with asymptotic scaling predictions. With Patrick Gallacher (visitor, NOARL) and Chin-Hoh

Moeng and John Wyngaard (both of MMM), McWilliams investigated surface wind stress and stable stratification.

Data Management and Visualization

Bryan, Holland, and student visitors Timothy Scheitlin and Mark Kessel (both of University of Colorado) continued development of advanced visualization tools for large-model data sets. The major emphasis during this period was the addition of both interactive and recorded animation capability to the OceanVu graphics system on the Stardent graphics supercomputer. They developed a number of tools to run on the UNICOS CRAY that facilitated generation of the large number of images required for animations of interesting lengths. The group produced a number of animations that generated considerable interest in the community as teaching tools and for research. Scientists in OS have also become peripherally involved in a joint NCAR/IBM project to develop database management systems for NASA's Earth Observing System (EOS) Program. The WOCE CME data archive is a test bed for a prototype system. Initial work focused on efficient data structures for storing large data sets.

Ocean Observations

OS scientists are involved in several projects that contribute to national and international efforts aimed at obtaining and utilizing routine global measurements of ocean-forcing functions and dynamical quantities. Holland and Large, with James Evans (University of South Carolina), continued their study of the effect of satellite scatterometer wind sampling on ocean response as part of the Science Definition Team for NASA's scatterometer project (NSCAT). In a related activity, Large deployed at sea two different systems for oceanic wind-stress measurements in the Surface Wave Dynamics Experiment. The data are to be used to ground-truth airborne scatterometer measurements.

Holland continues his participation in NASA's Topography Experiment (TOPEX). The assimilation of satellite altimetric data into ocean numerical models and the analysis of altimeter observations, with Lee Fu and Victor Zlotnicki (both of NASA's Jet Propulsion Laboratory), are showing great promise in reproducing actual oceanic eddy behavior. Effective data-assimilation schemes that make use of a variety of ocean data, in collaboration with Paola Malanotte-Rizzoli (MIT), continue to be important activities as the launch of TOPEX approaches.

One promising source of global forcing for ocean models is the analyzed fields from operational forecast models. Large and Trenberth used these fields from the ECMWF over the 1980s to quantify globally the annual cycle of wind stress. In particular, the first two annual harmonics are related to persistent meteorological features such as the Aleutian Low. Large and Trenberth prepared the derived field of wind stress and wind-stress curl for general distribution.

In October 1989, a large array of 20 thermistor-chain drifters was deployed in the western equatorial Pacific Ocean as part of TOGA. This research effort is a collaboration of Large and McWilliams, with Bruce Taft and Michael McPhaden (both of NOAA's Pacific Marine Environmental Laboratory) and Peter Niiler (SIO). The array was short-lived but successfully captured the ocean's response to a strong westerly wind burst in late 1989. They will use these data to evaluate numerical model simulations of the event.

After many years of planning, OS scientists are preparing for the five-year observational phase of WOCE. Large is participating in a major Canadian contribution to the WOCE/TOGA Surface Velocity Project with Paul LeBlond (University of British Columbia, Vancouver), Richard Thomson (Institute of Ocean Sciences, Patricia Bay, British Columbia), Gordon Swaters (University of Alberta, Edmonton), and David Krauel (Royal Roads, Victoria, British Columbia). The first of a planned five-year array of mixed-layer drifters was deployed in the Gulf of Alaska. Regular mapping and intensive observational arrays are planned with the objective of determining the mean state and interannual variability of the Alaskan Gyre. OS scientists will combine the data with other WOCE efforts to provide complete five-year coverage of the entire north, south, and equatorial Pacific Ocean. Because of the direct relevance to ocean modeling, OS scientists are interested in WOCE global data sets, including sea surface altimetry from TOPEX and surface wind stress from NSCAT, and in Core III studies in the Atlantic.

Coupled Models

Gent and Tribbia continued work on a coupled model to study ENSO phenomena. The coupled model consists of an aquaplanet version of the CCM coupled to the equatorial model in a rectangular basin. A first long 12-year run gave very encouraging results in that the climate drift in the model was very small and the model had realistic annual and interannual variability. The model will be changed to use the updated version of CCM2 in the near future.

Holland and Bryan, with Williamson, began a multiyear project of air and sea interaction in which they will couple the oceanic CME model of the North Atlantic to the atmospheric CCM2 global model. The first assessments will be concerned with the apparent flux imbalances of heat, fresh water, and momentum that each component model sees in the uncoupled mode when forced by observed conditions at the interface. Both the CCM2 and CME are new models with improved physics, and the hope is that the serious mismatch of previous coarser-resolution models will no longer be as important.

Global Dynamics Section

The objective of GDS research is to understand the causes and theoretical predictability of low-frequency planetary-scale atmospheric variability on time scales of days to months, in order to contribute to prediction of the transient behavior of low-frequency planetary-scale circulations in the coupled atmosphere-ocean system. GDS scientists take three approaches to their research: (1) development and application of a coupled atmosphere-ocean model to investigate low-frequency variability, such as the ENSO phenomenon; (2) design of strategies for prediction of low-frequency variability and experimentation with the CCM to explore the practical skill of predicting low-frequency variability; and (3) investigation of the cause of tropical forced low-frequency atmospheric oscillations, including the role of diabatic heating on the irrotational (Hadley-Walker) circulations, and the interactions between the midlatitude and tropical circulations. To comprehend the essential aspects of the diagnostic and experimental findings, GDS scientists complement observational and numerical studies through theoretical studies with simpler atmospheric models.

Understanding the Mechanism of the ENSO Phenomenon

Tribbia and Yen-Huei Lee, in collaboration with Gent and Brian Kauffman, have been developing a coupled ocean-atmosphere model suitable to study the dynamical mechanisms leading to the ENSO phenomenon. The atmospheric model was simplified only in its treatment of radiative fluxes and the elimination of continentality. These simplifications reduce computational costs and elucidate the dynamical essence of the ENSO cycle. The ocean model is a primitive-equation, upper-ocean model of an idealized equatorial Pacific basin. Tribbia and Lee found that the coupled system was very sensitive to the prescription of the surface-drag coefficients and, thus, some tuning of the roughness length was necessary in the idealized configuration. To date, the coupled model has been integrated for 15 years, and during this period the system has produced reasonable annual and interannual variability. With the advent of the CRAY Y-MP, scientists are investigating the parametric dependence of simulated ENSO variations on the air-sea exchange coefficients, the ocean basin size, and the role of continentality. In addition to ENSO simulations, they plan studies to ascertain the dynamical predictability of the ENSO cycle and the midlatitude anomalies induced by the equatorial circulation changes inherent in this cycle with a version of the coupled system that incorporates realistic continentality and oceanic boundaries.

Mechanisms of Low-Frequency Variability

A noteworthy characteristic of atmospheric flow is that a large fraction of low-frequency variance can be represented by just a few structures. As a step toward understanding what causes these special patterns, Branstator and Andrew Mai undertook a linear budget study for each recurring pattern in an extended control run of the CCM. Two major energy sources exist for these patterns—transient eddy fluxes in the storm-track regions and interactions between the flow anomalies and the time-mean circulation. Interestingly, the model atmosphere is not able to use the most efficient means available to maintain the patterns because the locations in which the patterns are most easily excited do not coincide with source regions. Preliminary results suggested that a symbiotic relationship may exist between the low-frequency anomalies and high-frequency transients. Not only do the transients help to maintain the slow anomalies, but the low-frequency anomalies may organize the transients. This latter relationship is suggested by ongoing calculations of the fastest-growing modes of the CCM linearized about states that include observed low-frequency anomalies.

In collaboration with Trenberth, Branstator extended his investigation of possible causes of the North American drought of 1988. Previous work indicated that the drought pattern could have been initiated by rainfall anomalies in the subtropical eastern Pacific. More recent diagnostic calculations supported the impression from outgoing long-wave radiation maps that, in addition to heating anomalies in the Pacific, there were also heating anomalies over North America that may have maintained the circulation associated with the drought. Experiments with a linear planetary-wave model indicated that the response to these midlatitude anomalies would have constructively interfered with the flow stimulated from the tropics but alone could not have been responsible for the entire flow pattern during the drought episode. The results were consistent with the notion that midlatitude feedback mechanisms acting through moist processes could have played a role in maintaining the drought.

In collaboration with Anthony Hansen (Control Data Corporation) and Alfonso Sutera (Yale University), Tribbia studied the ability of the climate models (CCM0 and CCM1) to reproduce the observed bimodality of the SH winter flow. Tribbia and collaborators found that, despite the rather small differences in the physical parameterizations in the two model versions, a significant difference exists in the ability of these two models to reproduce the observed low-frequency variability. In spite of the nearly identical reproduction of the mean SH winter state, they found that only the CCM0 was able to reproduce the variability about this state associated with planetary-wave bimodality. They are investigating the physical explanation of this result, but preliminary results suggest that the weaker-than-observed high-frequency transients in the CCM1 are responsible for its lack of bimodal behavior.

Predictability of Low-Frequency Variability

In order to review progress in long-range prediction, David Baumhefner and Maurice Blackmon (Environmental Research Laboratory, NOAA) organized the

Workshop on Numerical Long-Range Prediction of 10- to 90-Day Time-Mean Flows at NCAR in June 1990. Workshop discussions included assessment of current skill, identification of fundamental problems and new approaches, and coordination of future joint experimental designs. On average, 30-day forecast skill is marginal, but a significant number of forecasts are successful in both the midlatitudes and the tropics. So far, prediction of forecast skill has not been very successful. Forecast skill is remarkably sensitive to variations in initial data and lower boundary specifications and to changes in model formulation. Systematic error is still a major contributor to inaccurate forecasts. Discussions of the nature of atmospheric variability and the ultimate predictability of low-frequency flow were optimistic—tempered, however, with lack of knowledge of scale interactions with higher-frequency baroclinic systems. The participants agreed on the major difficulties facing long-range prediction and endorsed collaborative work on common forecast experiments.

To investigate long-range prediction, Baumhefner evaluated a definitive experimental forecast data set for 30-day prediction, investigated the variability of forecast skill within this data set, and analyzed variability in the 10- to 30-day time scale, in models and the atmosphere. He and Thomas Mayer completed a data set of 30-day numerical forecasts for 49 independent cold-season situations selected from the last decade. The data set consisted of ten-member Monte Carlo forecast ensembles for each case, integrated with the CCM at T31 resolution. Baumhefner used the skill of this extensive sample of forecasts to determine the potential of long-range numerical prediction. For 30-day time means over the NH, 37% of the average forecasts in each ensemble were skillful. Regionally, 55% of the cases were skillful in the Atlantic–western European area, whereas only 39% were skillful in the Pacific–North American area. The 30-day skill was produced mainly by accurate 10-day mean forecasts in the first part of the period, but in 18% of the cases the second 10-day period was skillful as well. Verification of low-frequency variability in the tropics by Baumhefner, in collaboration with Madden and Hans von Storch (Max Planck Institute for Meteorology, Hamburg, Germany), showed considerable skill when 30- to 60-day waves were strong and active. These results clearly proved that extended-range forecasts are skillful for a significant number of occurrences. Their usefulness would be greatly enhanced by a priori estimates of their skill.

Baumhefner also examined the forecast data set for sensitivity of forecast skill to horizontal resolution and systematic error. He integrated 10 of the 49 cases at T42 resolution and noted that the average forecasts improved by 9% for 30-day means; however, 3 of the 10 samples did not improve. The second 10-day mean period actually improved more than the first 10-day skill. He calculated daily systematic (average) error for the 49-case data set, smoothed these values in time, and subtracted them from a subset of the forecasts. For the 11 cases that were only marginally skillful, removal of systematic error produced a 12% increase in skill for 30-day means. This increase brought the number of skillful cases to over 50% in the entire set. Cases in which skill was either very good or very poor did not react as favorably to a correction of systematic error.

Baumhefner, with Steven Mullen (visitor, University of Michigan), compared the characteristics of 10- to 30-day variability in the atmosphere with those in the climate simulation of the T42 CCM. They examined the excellent simulation of variability in the model in terms of synoptic components, such as regimes and blocking, and compared them to previous atmospheric analyses. The model's simulated blocking behavior was very good and will be used in a future set of predictability experiments.

Tribbia has furthered his investigation of the linearized approach to stochastic dynamic prediction (which seeks to utilize short time information on the evolution of the probability distribution in phase space) to initiate a Monte Carlo ensemble of small size. Tribbia's past efforts have shown that the eigenmodes of the symmetric linear problem, obtained by adding the linear-system matrix and its adjoint, gave optimal directions in phase space for distributing the ensemble elements. Tribbia showed that these directions corresponded to the principal directions of strain for the phase-space velocity advecting the ensemble elements and, thus, the most rapidly stretched axes of the probability distribution. Using these eigenstructures in a recent examination of the adequacy of random sampling, Tribbia showed that the probability of obtaining a representative sample of the 10 most important structures is less than 20% with an ensemble of 20 random-field realizations. This result has strong implications for the ability of the current techniques of Monte Carlo forecasting to accurately predict forecast skill.

There is a great deal of case-to-case variability in the skill of deterministic forecasts of the atmosphere. Reasoning that this may be the result of certain structures' being more easily forecast than others, Branstator and Mai began a study to determine which flow structures tend to be best forecast by numerical models. Examination of 3 winters of 8-day forecasts from ECMWF, as well as 53 extended-range forecasts produced by Baumhefner, showed that empirical orthogonal functions (EOFs) of observed states serve as a useful means of identifying the easily forecast flow components, and that the leading EOFs tend to be the most forecastable. Using this fact, Branstator developed a variational procedure to design optimal filters of instantaneous and time-average flows. These filters remove those components of the forecast that tend to be difficult to forecast. Cross-validation indicated that such filters can extend the usefulness of daily forecasts by about one and one-half days and, on average, increase the anomaly correlation score of monthly mean forecasts from .39 to .47, while retaining about 50% of the variance of the forecast fields.

Tropical Data Assimilation—Analysis of the Hadley Circulation

Errico initiated several joint research projects on various aspects of tropical data assimilation while on leave at NOARL under the UCAR/NOARL Visiting Scientist Program. With Nancy Baker (NOARL), Errico attempted to determine the variability of the mean meridional (Hadley) circulation on a day-to-day time scale. They concluded that the current observational network is insufficient to determine the strength of the Hadley circulation on such short time scales and, therefore, the noise in the Hadley circulation, which appears in numerical simulations, does not clearly indicate realism or error. With Ronald Gelaro (NOARL), Errico has been examining the model physics and dynamics that force high-frequency oscillations of the Hadley circulation in the NOARL global model. One exciting result, in both that model and the NCAR CCM, is an adjustment process which, at some scales, tends to regenerate any gravity-wave noise otherwise removed by initialization. Errico, with Thomas Rosmond (NOARL), compared analysis and initialization increments in the tropical temperature and pressure information with the implication that the tropical analysis of those fields is actually the model's first-guess field and, therefore, is strongly affected by the model climatology. Also with Rosmond, Errico examined the effects of topography on nonlinear normal mode initialization (NNMI), model balances, and determination of the pressure-gradient force. These results indicate that a major component of the so-called nonlinear balance of the external mode is due to the representation of the pressure-gradient force on sigma-coordinate surfaces.

Andrew Van Tuyl (visitor, NOARL) is investigating the problem of data rejection by data assimilation schemes in the tropics by exploring the feasibility and appropriateness of combining optimal interpolation (OI) and NNMI into one iterative procedure in the context of a shallow-water model. He is also investigating the tuning of various optimal-interpolation parameters within the tropics with the intention of developing an appropriate multivariate tropical OI scheme.

Solution to the Spin-Up Problem of Precipitation Forecasts

One deficiency of tropical weather forecasts is that numerical models are incapable of producing realistic tropical precipitation rates at the beginning of the model run. This is known as a "spin-up" problem and is caused, in part, by shortcomings in the initial specification of divergence, moisture, and temperature. Diabatic initialization successfully suppresses inertial gravity waves, but it cannot ameliorate the spin-up because (1) the diabatic information is inadequate for tropical initialization, (2) the moisture field is not initialized, and (3) the cumulus parameterization scheme is not initialized. Kasahara and Arthur Mizzi, in collaboration with Leo Donner (NCAR affiliate scientist from the University of

Chicago), developed a tropical initialization procedure that is divided into three components—application of diabatic NNMI, modification of the initial divergence by incorporation of satellite imagery data, and modification of the moisture and temperature fields by Donner's cumulus initialization scheme. They made many 10.5-h forecasts (42 time steps), starting from various initial conditions after application of some combinations of the three initialization components. They used a T42 version of the CCM1 and its associated NNMI package. The results of a case study show that (1) even if a good estimate of diabatic heating rates were available, diabatic NNMI alone would not solve spin-up; (2) the adjustments of moisture and temperature using the cumulus initialization are essential to ameliorate spin-up; and (3) the divergence adjustment, assisted by satellite imagery data, is beneficial when used in conjunction with the cumulus initialization and diabatic NNMI procedures.

Dynamical Aspects of Atmospheric Circulations

In recognition of Philip Thompson's significant scientific achievements and long-term contributions to scientific leadership at NCAR to encourage physicists and mathematicians to work in atmospheric science, CGD established a one-year visiting scientist position. The first recipient of this special appointment is Jeffrey Weiss, who is working on application of nonlinear dynamics and chaos to the understanding of atmospheric and oceanic flows.

With Richard Grotjahn (University of California, Davis) and a student (Min Chen), Tribbia has investigated the role of continuum modes in the growth of arbitrary baroclinic disturbances in atmospheric models with small internal dissipation. Brian Farrell (MIT) expounded on the efficacy of continuum modes in representing rapid growth within the context of internally inviscid atmospheric flows. However, because of the likely strong effect of internal dissipation on the continuous spectrum, Tribbia and collaborators studied the eigenvalue problem with dissipation. They showed that the viscously modified continuum modes were indeed vigorously damped in the presence of realistic values of internal eddy viscosity and, thus, have reopened the question of the practical relevance of the continuous spectrum.

Errico worked with Tomislava Vukicevic (ASP postdoctoral fellow) on development of an adjoint version of the mesoscale model version 4 (MM4). As of December 1990, the adjoint is producing results and they plan to use it to interpret predictability studies, to perform sensitivity and stability analyses of the MM4, and to apply it to problems of data assimilation.

Errico worked with Mingxuan Chen (visitor, Academy of Atmospheric Science, Beijing, People's Republic of China) to develop a method of generating time series of precipitation that are valid on the mesoscale but determined from the coarse-resolution CCM. The method uses linear regression applied to results from the NCAR regional climate model to determine statistical interpolation relationships. It works quite well, and some simple improvements should make it a cheap replacement for very long integrations of the more complex regional climate modeling system.

Environmental and Societal Impacts Group

The research activities of ESIG are geared toward developing insights into how societies might better understand and cope with the interactions between human activities and atmospheric processes. ESIG continues to categorize its activities into three areas: research, linkage, and outreach. Research is undertaken by group members individually or with others in the group or in other divisions within NCAR; linkage refers to collaborative research with others at universities and in government organizations; outreach pertains to lectures, workshops, symposia, and fellowships under the auspices of ESIG members. ESIG's activities fall into the areas of interactions of climate and society and the value and use of meteorological information.

Regional Scenarios Project

Glantz researched the use of analogies in the physical and social sciences with respect to the global warming issue. This is an expansion of his work on forecasting by analogy, designed to determine levels of societal ability to cope with climate-related environmental change. The forecasting-by-analogy approach is dependent on historical analogies. Glantz's research includes interviewing atmospheric scientists about the use of paleoclimatic reconstructions, parameterization processes in modeling activities, and contemporary warm decades or years in a search for analogs of what changes might be expected as the result of a global warming. Each attempt at a glimpse of the future has its strengths and weaknesses. Analogs are put forth for a variety of reasons—hypothesis generation, public education, understanding physical processes—and their purpose must be explicit. While the Altithermal, for example, might generate useful insights into a variety of aspects of global warming and is a useful analog in this context, it is only one of many future possibilities and, therefore, is not very useful for policymaking. This project will continue into FY 91 with a focus on analogies in the ocean sciences with respect to global warming.

Glantz also coordinated, with the support of Lucy Feingold (visitor, University of Delaware), the ESIG/National Marine Fisheries Service/EPA project called Climate Change, Climate Variability and Fisheries. This multinational and multidisciplinary project used 15 historical analogies to ascertain the levels of resilience and vulnerability of fisheries to changes in abundance or availability of living marine resources. A summary report has been prepared, and Glantz will edit the full-length papers to be published by Cambridge University Press.

Within the above project, Glantz undertook a study of the Anglo-Icelandic Cod Wars (1952–76) as an analogy to the possible societal consequences of a shift in fish populations due to a global warming. Feingold researched the development of the menhaden fishery along the Atlantic Coast and the response of that fishery to climate variations. Kathleen Miller, in cooperation with David Fluharty (University of Washington), examined the evidence of climate-related variations in salmon productivity in the Pacific Northwest. They also investigated the socioeconomic impacts of the poor runs in the Pacific Northwest and California in 1983 and 1984 related to the 1982–83 El Niño. The poor harvests culminated a multiyear declining trend for Chinook salmon in British Columbia, Washington, and Oregon and for Coho salmon in Washington, Oregon, and California. In 1983, Washington's harvest of Sockeye salmon was also adversely affected by changes (apparently El Niño–related) in the migration route of Sockeye returning to the Fraser River (British Columbia). Whereas considerable evidence exists that climate-related variations in marine conditions and riverine environments have a substantial effect on the productivity of individual salmon stocks, numerous compounding factors make it difficult to establish clear relationships. The socioeconomic impacts of these variations are similarly complex. In the 1982–83 El Niño, the distress associated with the poor runs of Coho and Chinook in 1983 and 1984 was compounded by regulatory changes aimed at protecting the Indian fishery and by unusually low prices for salmon arising from very large salmon runs in Alaska (part of an increasing trend in Alaskan salmon production).

Climate Change and U.S. Water Institutions

Global warming may have major impacts on water availability, with possible reductions in supplies in some regions. The socioeconomic impacts of such changes will depend on the nature of the institutions governing the allocation of water among competing users and on the adaptability of these institutions. Miller has focused on the issue of the adaptability of U.S. water institutions to possible reductions in water supplies, comparing the riparian and permit systems followed in the eastern United States with the prior-appropriation system followed in the western United States.

The experience of the western states suggests that flexibility can be created through the use of transferable rights measured on the basis of consumptive use. As demand for water has increased in the western states, there have been efforts to improve the transferability of water rights by statutory changes and to clarify their ownership and definition by court adjudications. In addition, attention has increased in protecting public and third-party interests relating to changes in water use. This process of institutional adjustment has been costly, time-consuming, and subject to conflict, however.

In the eastern states, water rights cannot be freely transferred among users in response to changes in water availability. Water users face considerable uncertainty on how water will be allocated under drought conditions, and the permit systems adopted in these states have done very little to resolve that uncertainty. The possibility that water may become less abundant in these states in the future, due to climate change, suggests the importance of further reforms.

In another project investigating the potential response of water institutions to climate change, Steven Rhodes and Miller, in collaboration with Lawrence MacDonnell (University of Colorado), made substantial progress on a case study of regional adjustments to climate change–induced reductions in municipal water supply. Using forecasting by analogy, the collaborators are studying the responses of water-provider organizations in the Denver metropolitan area to the veto by the EPA of a large dam and reservoir that would have augmented the region's water supply well into the next century. The loss of this future storage project is prompting water-provider organizations to make decisions for ensuring adequate water supply for the next several decades. These include accelerated conservation measures and revised pricing, acquisition of agricultural water rights by cities, and new proposals for large-scale interbasin water transfers to serve the populated Front Range of Colorado. This context of loss of a large water-storage project and regional institutional responses is analogous to what may occur as a result of climate change over a period of decades. Responses have been cooperative as well as conflictual. As a regional analog to possible climate change impacts, the Denver metropolitan area's responses to the veto of the large storage project provide a living laboratory for assessing how well (or how poorly) societal institutions may adapt to changing resource availability in the future.

Extreme Meteorological Events and Climate Change

Richard Katz and Barbara Brown are principal investigators in a three-year project funded by the EPA called Methods for Analyzing Extreme Events with Application to Scenario Development for Climate Impact Assessment. In the second year of the project (FY 90), they concentrated on extending their theoretical results on how the probability of occurrence of extreme events would change as the average and variability of climate change in situations that are more realistic for climate variables. These extensions involved allowing for the temporal correlation of climate time series and for the fact that extreme values are usually based on relatively small samples. The theoretical result was quite robust, i.e., the relative sensitivity of extreme events to the average or variability of climate was greater the more extreme the event.

The ESIG/Hungarian Meteorological Service joint project on identifying and coping with extreme meteorological events was completed with the final workshop at NCAR in October. This three-year study (delayed several months by political changes in Eastern Europe) produced several workshops and publications and identified research areas for future collaborative activities, several of which are being pursued. In addition to six Hungarian scientists, participants included researchers from ESIG, the University of Minnesota, and the University of Nebraska. Related work included the preparation with Tibor Faragó (Hungarian Meteorological Service, Budapest) of a WMO report entitled Extremes and Design Values in Climatology. A final report will be submitted to the funding agencies—the NSF Division of International Programs and the Hungarian Academy of Sciences.

Economic Adjustment to Perceived Climatic Risks

Climate information is important for investment decisions in many fields (agriculture, water, energy, etc.), and uncertainties about climatic change put a new burden on planners. To be most useful to decision makers, projections of climatic change must include information related to specific climate risks, many of which involve extreme events. A change in the apparent freeze risk in Florida due to a series of severe freezes in the 1980s is an example of the importance of climate variability and potential climate change in investment decisions.

To identify climatic factors associated with the apparent change in freeze risk, Mary Downton examined the influence of several atmospheric circulation patterns on winter temperatures in Florida. The Pacific–North American pattern was particularly influential and the North Atlantic Oscillation significant, while the Southern Oscillation did not show a direct effect. A decreasing trend in Florida winter temperatures since 1947 could be explained by fluctuations in the former two circulation patterns. It is argued that climate model studies of possible changes in the frequency or location of these circulation patterns could suggest potential changes in the freeze risk associated with global warming.

Miller studied the multiple factors that influence the investment decisions of citrus growers and the role of freeze risk in that decision. She developed a simple model to estimate tolerable levels of freeze risk and to show the impact of changes in the risk level, and she then related it to growers' replanting decisions in response to the freezes of the 1980s.

In a related project, Miller applied portfolio theory to the Florida citrus-investment problem. Economic models of investment behavior imply that individuals diversify their asset portfolios to achieve a desired balance of perceived risks and expected returns. It was hypothesized that the recent series of severe freezes in Florida may have reduced the expected returns and increased the perceived risk of investments in Florida citrus groves, particularly for the varieties most susceptible to freeze damage. This would be expected to lead to changes in the spatial distribution and varietal composition of new planting activity. Miller completed a project using portfolio theory to analyze the replanting behavior of Florida citrus growers following the freezes. The empirical evidence supports the joint hypothesis that growers diversify their investments in a manner consistent with portfolio theory and that they have updated their climate expectations in response to the 1980s freezes.

Glantz organized a workshop (jointly funded by NSF and the United Nations Environment Program, or UNEP) in Malta in June "On Assessing Winners and Losers in a Global Warming Context," with Martin Price (visitor, University of Colorado) as rapporteur-participant. The focus of the workshop was on whether appropriate objective measures exist for identifying advantages and disadvantages that might be associated with a global warming. There are many statements about losses and gains that might result, but little attention has yet been given to the meaning of a win, loss, advantage or disadvantage. A little less rain does not necessarily translate into a loss any more that a little more rain converts directly into an advantage. These changes must be objectively evaluated in regional and local contexts.

The Republic of Malta, host of the workshop, has been active for decades in the protection of the global environment. The multinational and multidisciplinary workshop included participants from Bangladesh, the Caribbean community, Brazil, France, Germany, Hungary, Malta, Kenya, the United States, and the USSR, representing the fields of political science, economics, meteorology, environmental ethics, biology, and environmental law. The participants concluded that there is a need to develop objective measures of the impacts of climate change on societies in order to remove the issue of advantages or disadvantages from the realm of speculation. Such measures are also important for use in climate impacts research activities, climate change notwithstanding.

Political and Legislative Control of Global Air Pollution

Rhodes and John Firor (ASP) studied recent historical successes in controlling global air pollution at international, national, and even local levels of political organization. They looked at the Nuclear Test Ban Treaty of 1963 as a prototype multilateral agreement to protect the atmosphere; the NH international treaty on the long-range transport of air pollutants; the U.S. Clean Air Act, which became a model for other national air-quality-control programs; the Montreal Protocol and local actions to accelerate the phase-out of stratospheric ozone-depleting chemical compounds; and more recent efforts to control and reduce global emissions of other greenhouse gases, most notably CO_2. They concluded that addressing atmospheric protection in a segmented manner is more likely to produce a broad political consensus and international and national support than comprehensive treaties and conventions aimed at regulating many issues simultaneously. (Their study is presented in *Global Atmospheric Chemical Change*, Elsevier Scientific Publishers Ltd., 1991.)

Global Desertification

Rhodes aggregated past and recent literature on the state of global desertification in order to organize contemporary critiques of conventional wisdom on the state of dryland degradation around the globe. Although to date only a few analysts have openly challenged the conventional wisdom (allegedly perpetuated by the United Nations), 20 years of desertification research have produced reasons for reassessing what is thought to be known about this global environmental issue. These include (1) problems associated with multiple definitions of desertification, since definitions force conclusions about causes, impacts, and solutions, as well as estimates of how much land surface has been so degraded; (2) questionable baseline information about the history of the world's drylands, particularly with respect to distinguishing between the effects of drought and long-term environmental change; (3) overreliance on early assumptions and estimates of global desertification; and (4) recent findings from remote sensing and long-term land-surface monitoring that challenge previous research conclusions about the state of dryland resources.

Statistical Evaluation of GCM Experiments

Katz, while on sabbatical at the University of California, Davis, evaluated statistical methods for quantifying the uncertainty in the outcomes of GCM experiments for the Lawrence Livermore National Laboratory Program for Climate Model Diagnosis and Intercomparison. In his review of the already extensive literature on this topic, he concluded that (1) there is a preoccupation with hypothesis testing, whereas other methods (such as confidence intervals) would be more appropriate for characterizing the uncertainty of GCM output; and (2) virtually all of the GCM output to date has been produced by experiments whose design evidently does not reflect any consideration of statistical issues. Conclusion (1) is related to the issue of interpreting the GCM output in a form that is most convenient for users, and conclusion (2) explains why questions of interest to the impacts community, such as whether climate variability or the frequency of extreme events has changed, typically draw inconclusive answers.

Networking

A major concern of ESIG for the past few years has been the development of a community of researchers concerned with the interaction between climate and society. The generation of awareness of the importance of climate-related phenomena has broadened the disciplinary involvement in research on climate-related topics and has identified new researchers willing and able to contribute to this field. ESIG activities included the continuing publication, with some financial support from the UNEP, of a quarterly climate-impacts-related newsletter (distribution around 1500), as well as an active national and international visitor program.

Interdisciplinary Climate Systems Section

ICS scientists conduct research on the relationships between climate change and global environmental systems. Their emphasis is on the coupling of the atmosphere with such systems as the biosphere, soils, sea ice, and chemistry. Although ICS scientists, of necessity, must develop research in specialized disciplinary areas, such as land-surface processes or sea ice (and indeed will make such packages available to the CCM effort), their primary goal is the study of the evolution of climate change on decadal or longer time scales, with emphasis on coupling to soil or biological systems and paleoclimatic analysis. For these purposes, high-resolution GCMs are simply impractical because they cannot be run over the many-decade time scales needed for meaningful equilibrium or transient runs. For example, forests require hundreds of years to reach equilibrium and, therefore, runs of even a few decades are not useful in these applications.

Global Environmental and Ecological Simulations of Interactive Systems

ICS scientists chose to optimize a low-resolution version of the CCM1, having completely recoded and directed it toward emphasis on surface processes, future coupling of biospheric processes, and paleoclimatic simulation. The ICS model—Global Environmental and Ecological Simulation of Interactive Systems (GENESIS)—is undergoing finishing touches and tuning in preparation for a frozen version to be available to interested users in the ecological, paleoclimatic, or other scientific communities by spring of 1991. It includes a land-surface transfer scheme built on the pioneering work of Dickinson's BATS and Piers Sellers's (NASA Goddard Space Flight Center) simple biosphere (SiB), as well as a simple ocean mixed layer with Q-flux option and fully dynamical sea ice. To permit easy modification for biospheric or other packages by those not highly skilled in coding techniques, ICS scientists recoded the model to be core-contained.

Under the direction of Starley Thompson, Pollard developed a package of surface-process models to be included in GENESIS. The surface models all use a $2° \times 2°$ grid, and fields are transferred to and from the CCM's R15 grid by straightforward area averaging or interpolation at each time step. The surface models include:

- A model of vegetation and its effects on the surface fluxes, with separate upper and lower canopies representing trees and grass. The physical design is close to the SiB model, but with less mathematical complexity. The model currently uses the global vegetation data set of Dorman and Sellers.

- A treatment of sea-ice advection using the cavitating-fluid model of Flato and Hibler. Along with Peter Rayner (visitor, Commonwealth Scientific and Industrial Research Organization, Mordialloc, Australia), Pollard adapted Flato and Hibler's published model for use with ICS's longitude-latitude global grid and multilayer ice model. The addition of dynamics strongly affected and improved the model sea-ice extents around Antarctica. Sea ice is driven from below by prescribed ocean surface current fields obtained from results of Semtner and Chervin's $1^\circ \times 1^\circ$ ocean GCM.

- Standard thermodynamic multilayer models of soil, snow, and sea ice. The soil model has six layers and includes nonlinear soil-moisture diffusion and permafrost.

- A thermodynamic 50-m slab of water representing the ocean's mixed layer.

The R15 CCM version is core-contained (uses global arrays). Other changes from the standard CCM1 include semi-Lagrangian transport of water vapor, implemented from code provided by Rasch and Williamson; a diurnal cycle, with solar calculations performed every 1.5 h and IR calculations performed every 0.5 h, except for the costly calculation of IR absorptivities once a day; and provision for differing orbital elements at any specified time in the Pleistocene.

The coupled model has been run for several decades in the course of tuning to the present climate, and a control version will be frozen in the spring of 1991. Planned experiments include greenhouse-induced changes to the global vegetation and various paleoclimatic situations.

Model and Observational Intercomparisons for Daily Variability Diagnostics

Under the direction of Linda Mearns and in collaboration with Schneider and Thompson, the analysis of daily variance in both nature and general circulation models is continuing.

Mearns and collaborators analyzed variability statistics for climate variables relevant to climate impact analysis produced by GCMs (CCM), by focusing more on determining the proper match between observational data and GCM grid-box output. This entailed statistical analysis of changing properties of the observational data as the number of stations used and averaged was incremented. This proved useful in determining the appropriate number of stations for model and observation comparisons (in this instance for grid boxes located in the United States). Further research on this in other areas of the world is continuing. Larry McDaniel assisted on this project.

Mearns's investigation of the comparative success of different versions of the CCM in reproducing important aspects of the Indian monsoon is under way. This has involved the development, with McDaniel, of a very detailed daily precipitation observational data set which should prove useful to the modeling community at large. Significantly, the Dickinson version of CCM1 (prescribed SST and mixed-layer versions) is more successful at reproducing the major features of the monsoon than other versions of the CCM (such as the standard CCM1). Thompson, Pollard, and Schneider are looking at the reasons for these differences.

In conjunction with the EPA, Mearns developed some basic scenarios of possible variance change for use in international climate change agriculture projects. This entailed analyzing ranges of variance change in observational data and a number of model runs to come up with reasonable ranges of plausible variance change for sensitivity analyses.

Mearns initiated a third small project involving analysis of seasonal variance change of temperature in different parts of the world. The initial motivation for this work was to evaluate the validity of the so-called summer analog of CO_2 warming—that summerlike conditions would prevail and, hence, variability would decrease. Her preliminary analyses indicate that summer interannual and daily variance is not always lower than that of winter (Southeast Australia is a case in point). Mearns will continue this research by examining other climate regimes in other regions of the world.

Embedding the Mesoscale Model into a GCM

Because biological or hydrological impact assessments require regionally detailed climatic scenarios, ICS scientists have invested considerable resources in bridging the scale gap between the GCM grids and local applications.

Filippo Giorgi developed and tested the nested CCM1-MM4 regional climate modeling system over the western United States, in collaboration with Gary Bates and Steven Nieman. Most of the year has been devoted to development of model parameterizations and to model verification. They implemented modifications to the Kuo-type cumulus parameterization in the standard MM4 to reduce the occurrence of numerical point storms during summertime simulations. These modifications consisted of allowing slower release of condensational heating and cumulus moistening during convective activity, and they have ameliorated considerably the problem of numerical point storm occurrence.

Giorgi completed a 2-year simulation (1982–83, i.e., a wet period over the western United States) and a 1.5-year simulation (January 1988–April 1989, i.e., a dry period over the western United States), with the MM4 driven by ECMWF analyses for the western United States. Analysis of these runs is under way and includes validation of model climatology (precipitation, surface air temperature, and snow cover) and BATS hydrology (evaporation and runoff) against station observations. McDaniel is assisting in development of the observational data set.

Giorgi implemented a new boundary-layer scheme into the MM4. This scheme, developed originally by Holtslag (also used in the CCM2), allows more efficient detrainment from the boundary-layer top, compared with purely diffusive boundary-layer formulations.

In collaboration with Mearns and Bates, Giorgi applied the nested CCM1-MM4 modeling system to regional climate simulation over the Great Lakes Basin. MM4 test simulations over the Great Lakes Basin will assess the model sensitivity to horizontal resolutions ranging from 30 to 90 km. Giorgi is assessing the performance of various versions of the CCM (Washington-Meehl, Dickinson, and Thompson-Pollard) to select the most suitable one to use for MM4 nesting over the area. Also with Mearns, Giorgi conducted extensive research on regional climate modeling techniques.

Giorgi, with Guido Visconti and Maria Rosaria Marinucci (both of the University of L'Aquila, Italy), applied the nested CCM1-MM4 model system to regional climate simulation over western Europe. He has carried out a number of MM4 summer- and wintertime simulations with lateral boundary conditions provided by ECMWF analyses and compared them to observations to study model sensitivity to selected precipitation parameterizations and lower boundary conditions. The model reproduced realistic synoptic systems, and the model precipitation and surface air temperature biases were within reasonably small ranges (a few kilometers and 10–25% precipitation biases). He is analyzing for MM4 nesting current climate and $2 \times CO_2$ simulations with the Washington-Meehl version of the CCM0 (coupled mixed-layer runs).

In collaboration with Ann Henderson-Sellers and Andrew Pitman (Macquarie University, New South Wales, Australia), Giorgi applied the nested CCM1-MM4 model system to regional climate simulation over southeastern Australia. He performed and is analyzing month-long simulations over southeastern Australia with the MM4 nested in the CCM1.

With Steven Hostetler (visitor, U.S. Geological Survey, or USGS), Giorgi studied the effects of large paleolakes in the southwestern United States on local climate by performing preliminary winter- and summertime MM4 simulations of the possible effects of these paleolakes (Lake Lahontan and Lake Bonneville) on local climate and hydrology. They showed that lake-effect precipitation could have been important in maintaining the levels of the lakes. Also with Hostetler, Giorgi initiated coupling of more realistic surface runoff models to the MM4-BATS.

Giorgi and Patrick Kennedy have begun preliminary work for coupling BATS to CCM2.

Biosphere-Atmosphere Transfer Scheme

Over the last year, Dickinson (on leave at the University of Arizona) and Kennedy carried out numerical studies with their version of the CCM1 linked to the BATS land package and tuned to give global energy balance. They performed a control integration from which they archived the monthly average net energy fluxes at each ocean point. These were used as flux-correction forcing in further simulations with a mixed-layer ocean version of the code. They put considerable effort into treatment of the possible movement of the sea-ice margin away from the prescribed values in the fixed-ocean system. They are still analyzing the control and doubled CO_2 simulations carried out with this model over a limited period of time—a simulated 11 years. One notable deficiency is a shrinkage of sea ice to a much smaller cover than realistic. This is likely due, at least in part, to the model's deficit of clouds and excess of surface solar radiation during polar summer. With this code, they also performed integrations of the effect of Amazon deforestation and of a prototype treatment of vegetation that grows and decays interactively over the annual cycle. The latter integration needs to be repeated because of coupling errors in the code, but the Amazon deforestation study has produced some very interesting results. It shows, in particular, large decreases in rainfall over the Amazon, larger than decreases in evapotranspiration, so that runoff actually decreases.

This result is in agreement with the recent publications of Lean and Warrilow and Shukla et al., but it disagrees with previous results with CCM0 and an earlier version of the BATS code. They are pondering the reason for such a large change in the simulation results in moving between models.

Dickinson completed the execution-phase proposal for the EOS interdisciplinary investigation, which has now been funded.

Great Basin Paleoclimatic Studies

Larry Benson (USGS) and Hostetler used a physically based lake-thermal model and a model of lake level to associate late-Pleistocene lake-level chronologies of Lake Lahontan with repositioning of the polar jet stream. The lake-thermal model simulated late-Pleistocene evaporation rates as influenced by (relative to present) decreased air temperatures and increased cloud cover. Benson and Hostetler derived the air-temperature data used in the model from the geologic record. The model uses an assumed cloud cover, based on the simulated position of the polar jet stream atmospheric GCM paleoclimate experiments of Kutzbach and Guetter (both of the University of Wisconsin) from a present-day jet-stream-related cloud climatology. They used simulated evaporation rates (approximately 42% compared to present) in the lake-level model to simulate past lake levels and thus assess past hydrologic balances of Lake Lahontan. Hostetler also used a coupled lake and thermal-ice model to assess the possible impact of lake ice on late Pleistocene evaporation rates (and the hydrologic balance) of Lake Lahontan.

Hostetler and Giorgi completed preliminary experiments with the MM4 aimed at investigating the role that lake-atmosphere feedbacks (lake-effect precipitation) could have played in maintaining Lakes Lahontan and Bonneville during the late Pleistocene. Results indicate that lake-effect precipitation could have contributed to the water budgets of the Lahontan and Bonneville basins.

A detailed sensitivity analysis of the effect of changed climate variability on a deterministic crop model is under way. ICS scientists conducted the sensitivity analysis with climate data from Goodland, Kansas. Results so far indicate significant changes in the probability of crop failures with changed interannual variability of both temperature and precipitation when variance alone is changed. Interesting and somewhat counterintuitive results are obtained when the variance changes are coupled with mean changes, i.e., a variance decrease does not always mitigate a temperature increase, as has been claimed occasionally.

Interdisciplinary Climate Systems Workshops

Identifying topics and staff for studies over a broad range of disciplines is a formidable task. Therefore, ICS scientists rely heavily on visitors (especially ASP postdoctoral fellows), collaborators from university and government laboratories, and multidisciplinary workshops. For example, Schneider is the NCAR coordinator for CSMP and is working with the UCAR CSMP office to organize climate systems workshops. Annually, he organizes workshops sponsored by the U.S. Forest Service on topics related to forest and global change interactions. The ICS staff have agreed to plans for joint NCAR/EPA research projects in which forest and other ecological models will be coupled to GENESIS.

Staff and Visitors

Staff

Division Director's Office

Barbara Hill
Holly Howard
Ann Modahl
Warren Washington (director)

Division Office Systems Programmers
Elizabeth Coolbaugh
Karl Sierka

Climate Sensitivity and CO_2 Research Group
Thomas Bettge
Garrett Campbell (long-term visitor)
Robert Chervin
Gerald Meehl
Gary Strand
Lynda VerPlank
Warren Washington (leader)

Climate Modeling Section

Eileen Boettner
Byron Boville (deputy head)
Bruce Briegleb
James Hack
Rüdiger Jakob (student visitor)
Jeffrey Kiehl
Jerry Olson
Tamas Prager (long-term visitor)
Philip Rasch
Anthony Slingo (to 11 May 1990)
Piotr Smolarkiewicz (long-term visitor)
Andrew Van Tuyl (long-term visitor)
Mariana Vertenstein
David Williamson (head)

CCM Core Group
Linda Bath
Lawrence Buja
James Hack (leader)
James Rosinski
Gloria Williamson

Climate Analysis Section

Jeffery Berry
Dorene Howard
James Hurrell (long-term visitor)
Roland Madden (deputy head)
Chester Newton (long-term visitor)
Dennis Shea
Amy Solomon
Shoichi Taguchi (long-term visitor)
Kevin Trenberth (head)
Harry van Loon

Oceanography Section

Frank Bryan
Julianna Chow
Manuel Fiadeiro (long-term visitor) (to 24 August 1990)
Patrick Gallacher (joint long-term visitor with MMM) (to 1 April 1990)
Peter Gent
Emily Grimes
William Holland (head)
Brian Kauffman
Craig Kunitani (to 29 December 1989)
William Large
James McWilliams (deputy head)
Ralph Milliff (UCAR postdoctoral visitor)
Nancy Norton
LeAnne Schamp
Michael Spall (long-term visitor)

Global Dynamics Section

Ronna Bailey
David Baumhefner
Grant Branstator
Ronald Errico
Rex Fleming (long-term visitor)
Sue Haupt (joint long-term visitor with OS)
Akira Kasahara (head)
Yen-Huei Lee
Andrew Mai
Thomas Mayer
Arthur Mizzi
Philip Thompson (long-term visitor)
Joseph Tribbia (deputy head)
Jeffrey Weiss (long-term visitor)

Environmental and Societal Impacts Group

Barbara Brown
Mary Downton
Lucy Feingold (long-term visitor)
Daniel Gamachu (long-term visitor)
Michael Glantz (head)
Dale Jamieson (adjunct scientist)
Richard Katz

William Kellogg (adjunct scientist)
Maria Krens
Mark Meo (adjunct scientist)
Kathleen Miller (deputy head)
Martin Price (long-term visitor)
Steven Rhodes
Jan Stewart
Donald Wilhite (adjunct scientist)

Interdisciplinary Climate Systems Section

Gary Bates
Larry Benson (long-term visitor)
Jon Bergengren (long-term visitor)
Penelope Boston (long-term visitor)
Charles D'Ambra
Robert Dickinson (leave of absence)
Filippo Giorgi
Steve Hostetler (long-term visitor)
Patrick Kennedy
Maria Rosaria Marinucci (long-term visitor)
David Matthews (long-term visitor)
Larry McDaniel
Linda Mearns
Gudrun Nacke (long-term visitor)
Steven Nieman
David Pollard (long-term visitor)
A. Brewster Rickel (long-term visitor)
Mary Rickel
Stephen Schneider (head)
Stephanie Shearer
Starley Thompson (deputy head)
Francis Tower
Steve Welch (long-term visitor)

Affiliate Scientists

Leo Donner, University of Chicago
Dale Haidvogel, Johns Hopkins University
Karin Labitzke, Free University of Berlin
Albert Semtner, Naval Postgraduate School

Visitors

Albert Barcilon; Florida State University; 19 June to 31 August 1990; Global Dynamics Section

Aike Beckmann; Johns Hopkins University; 13 June to 3 August 1990; Oceanography Section

Karen Borza; University of Colorado; 1 September 1989 to 15 May 1990; Environmental and Societal Impacts Group

Mingxuan Chen; Academy of Atmospheric Science, Beijing, People's Republic of China; 1 December 1988 to 31 July 1990; Global Dynamics Section

Tsing-Chang Chen; Iowa State University; 5 to 31 July 1990; Global Dynamics Section

John Corbett; University of Minnesota; 28 August to 31 December 1990; Environmental and Societal Impacts Group

Piroska Csapo; Hungarian Meteorological Service, Budapest, Hungary; 1 February to 31 August 1990; Environmental and Societal Impacts Group

Lesley Ann Dupigny; McGill University, Montreal, Canada; 11 June to 14 September 1990; Climate Analysis Section

Alexander Fedotov; Shirshov Institute of Oceanology, Moscow, USSR; 2 to 29 April 1990; Oceanography Section

Robert Gardiner-Garden; University College, Australian Defense Forces Academy, Canberra, Australia; 1 to 30 April 1990; Oceanography Section

Susan Iott; University of Colorado; 11 June to 19 August 1990; Environmental and Societal Impacts Group

Gregory Jenkins; University of Michigan; 5 July to 4 August 1990; Division Office

Maureen Jordan; Colorado School of Mines; 1 July to 1 December 1990; Environmental and Societal Impacts Group

Vitaly Larichev; Shirshov Institute of Oceanology, Moscow, USSR; 3 April to 4 May 1990; Oceanography Section

John Latham; University of Manchester, England; 19 June to 20 July 1990; Climate Modeling Section

Dan Magraw; University of Colorado; 1 October 1989 to 30 September 1990; Environmental and Societal Impacts Group

Martin Miller; European Centre for Medium-Range Weather Forecasts, Reading, England; 5 March to 30 April 1990, Climate Modeling Section

Steven Mullen; University of Michigan; 1 June to 31 August 1990; Global Dynamics Section

Cynthia Nevison; Stanford University; 25 June to 20 December 1990; Division Office

Lee Panetta; Texas A&M University; 10 June to 20 August 1990; Oceanography Section

Peter Rayner; Commonwealth Scientific and Industrial Research Organization, Mordialloc, Australia; 1 June 1989 to 30 June 1990; Interdisciplinary Climate Systems Section

Jens Schroeter; Alfred Wegener Institute for Polar and Ocean Science, Bremerhaven, Germany; 1 April to 30 June 1990; Oceanography Section

Kathie Sharp; Metropolitan State College; 21 May to 29 June 1990; Division Office

Julia Slingo; European Centre for Medium-Range Weather Forecasts, Reading, England; 21 October 1988 to 8 June 1990; Climate Analysis Section

Lisa Sloan; University of Michigan; 27 June to 31 July 1990; Division Office

Laura Smith; Colorado State University; 13 February 1989 to 13 July 1990; Climate Analysis Section

Jacques Verron; Institute of Mechanics, Grenoble, France; 7 May to 16 June 1990; Oceanography Section

Guoxiong Wu; Institute of Atmospheric Physics, Academia Sinica, Beijing; 13 April to 18 May 1990; Global Dynamics Section

Publications

Refereed Publications

ANTHES, R.A., Y.-H. KUO, *E.-Y. HSIE, S. LOWNAM, and T.W. BETTGE, 1989: Estimation of skill and uncertainty in regional numerical models. *Q.J.R. Meteorol. Soc. 115*, 763–806.

*BARRON, E.J., *W.W. HAY, and S.L. THOMPSON, 1989: The hydrologic cycle: A major variable during earth history. *Palaeogeog., Palaeoclimatol., Palaeoecol. 75*, 157–174.

*____ and S.L. THOMPSON, 1990: Sea level and climate change. In *Studies in Geophysics*, National Academy Press, Washington, D.C., 185–192.

BATES, G.T., 1990: A case study of the effects of topography on cyclone development in the western United States. *Mon. Weather Rev. 118*, 1808–1825.

*BAUM, B., *W.B. KRANTZ, *J.H. FINK, and R.E. DICKINSON, 1989: Taylor instability in rhyolite lava flows. *J. Geophys. Res. 94*, 5815–5828.

BOVILLE, B.A., and D.P. BAUMHEFNER, 1990: Simulated forecast error and climate drift resulting from the omission of the upper stratosphere in numerical models. *Mon. Weather Rev. 118*, 1517–1530.

BRANSTATOR, G., 1989: Low-frequency patterns induced by stationary waves. *J. Atmos. Sci. 47*, 629–648.

BROWNING, G.L., W.R. HOLLAND, *H.-O. KREISS, and S.J. WORLEY, 1990: An accurate hyperbolic system for approximating hydrostatic and incompressible oceanographic flows. *Dyn. Atmos. Oceans 14*, 303–332.

*BUCHMANN, J., *J. PAEGLE, L. BUJA, and R.E. DICKINSON, 1989: Further FGGE forecasts for Amazon Basin rainfall. *Mon. Weather Rev. 117*, 1093–1102.

*CESS, R.D., *G.L. POTTER, *J.P. BLANCHET, *G.J. BOER, *A.D. DEL GENIO. *M. DÉQUÉ, *V. DYMNIKOV, *V. GALIN, *W.L. GATES, *S.J. GHAN, J.T. KIEHL, *A.A. LACIS. *H. LeTREUT, *Z.-X LI, *X.-Z LIANG, *B.J. McAVANEY, *V.P. MELESHKO, *J.F.B. MITCHELL, J.-J. MORCRETTE, *D.A. RANDALL, *L. RIKUS, *E. ROECKNER, *J.F. ROYER, *U. SCHLESE, *D.A. SCHEININ, A. SLINGO, *A.P. SOKOLOV, *K.E. TAYLOR, W.M. WASHINGTON, *R.T. WETHERALD, *I. YAGAI, and *M.-H. ZHANG, 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res. 95*, 16601–16615.

*CHEN, T.-C., *M.-C. YEN, and H. VAN LOON, 1989: The effect of divergent circulation on some aspects of the 1978/79 Southern Hemisphere monsoon. *J. Climate 2*, 1270–1288.

CHERVIN, R.M., 1990: High performance computing and the grand challenge of climate modeling. *Computers in Physics 4*, 234–239.

*COVEY, C., and S.L. THOMPSON, 1989: Testing the effects of ocean heat transport on climate. *Palaeogeog., Palaeoclimatol., Palaeocol. 75*, 331–341.

DICKINSON, R.E., 1990: Water and energy exchange. In *Remote Sensing of Biosphere Functioning* (R. Hobbs and H. Mooney, Eds.), Springer-Verlag, Heidelberg, Germany, 105–133.

____, R.M. ERRICO, F. GIORGI, and G.T. BATES, 1989: A regional climate model for the western United States. *Clim. Change 15*, 383–422.

*DONNER, L.J., and P.J. RASCH, 1989: Cumulus initialization in a global model for numerical weather prediction. *Mon. Weather Rev. 117*, 2654–2671.

ERRICO, R.M., 1989: The forcing of gravitational normal modes by convective heating. *Mon. Weather Rev. 117*, 2734–2752.

____, 1989: The degree of Machenhauer balance in a climate model. *Mon. Weather Rev. 117*, 2723–2733.

____, 1990: An analysis of dynamic balance in a mesoscale model. *Mon. Weather Rev. 118*, 558–572.

*FARAGÓ, T., *I. DOBI, R.W. KATZ, and *I. MATYASOVSZKY, 1989: Meteorological application of extreme value theory: Problems of finite, dependent and non-homogeneous samples. *Időjárás 93,* 261–275.

GENT, P.R., and J.C. McWILLIAMS, 1990: Isopycnal mixing in ocean circulation models. *J. Phys. Oceanogr. 20,* 150–155.

GIORGI, F., 1989: The climatological skill of a regional model over complex terrain. *Mon. Weather Rev. 117,* 2325–2347.

———, 1990: Sensitivity of wintertime precipitation and soil hydrology simulation over the western United States to lower boundary specifications. *Atmos.-Ocean 28,* 1–23.

———, 1990: Simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate 3,* 941–963.

GLANTZ, M.H., 1990: Desertification on the land and in the sea. In *Man and Marine Fishery Aquaculture and Ecosystems* (J.-P. Troadec, Ed.), Institut français de recherche pour l'exploitation de la mer (IFREMER), Paris, France, 655–679.

———, 1990: Assessing the impacts of climate: The issue of winners and losers in a global climate change context. In *Changing Climate and the Coast: Vol. 1, Adaptive Responses and The Economic, Environmental, and Institutional Implications* (J.G. Titus, Ed.), Report of the Intergovernmental Panel on Climate Change, Washington, D.C., 125–137.

———, 1990: Drought, famine, and the seasons in sub-Saharan Africa. In *Anthropological Perspectives on the African Famine* (R. Huss-Ashmore and S. Katz, Eds.), Gordon and Breach Science Publishers, New York, N.Y., 45–71.

*GRAHAM, N.E., *T.P. BARNETT, *V.G. PANCHANG, *O.M. SMEDSTAD, *J.J. O'BRIEN, and R.M. CHERVIN, 1989: The response of a linear model of the tropical Pacific to surface winds from the NCAR general circulation model. *J. Phys. Oceanogr. 19,* 1222–1243.

*———, *———, R.M. CHERVIN, *M.E. SCHLESINGER, and *U. SCHLESE, 1989: Comparisons of GCM and observed surface wind fields over the tropical Indian and Pacific Oceans. *J. Atmos. Sci. 46,* 760–788.

HACK, J.J., and *W.H. SCHUBERT, 1990: Some dynamical properties of idealized thermally-forced meridional circulations in the tropics. *Meteorol. Atmos. Phys. 44,* 101–118.

*HAY, W.W., *E.J. BARRON, and S.L. THOMPSON, 1990: Results of global atmospheric circulation experiments on an earth with a meridional pole-to-pole continent. *J. Geological Soc. 147,* 385–392.

*HELM, J.L., and S.H. SCHNEIDER, 1990: What to do about CO_2. In *Energy: Production, Consumption and Consequences,* National Academy Press, Washington, D.C., 213–237.

HERRING, J.R., and J.C. McWILLIAMS, Eds., 1989: *Lecture Notes on Turbulence: Lecture Notes from the NCAR-GTP Summer School, June 1987,* World Scientific, Singapore, Malaysia, 371 pp.

HOLLAND, W.R., 1989: Altimeter data assimilation into ocean circulation models—Some preliminary results. In *Oceanic Circulation Models: Combining Data and Dynamics* (D.L.T. Anderson and J. Willebrand, Eds.), Kluwer Academic Publishers, Dordrecht, The Netherlands, 203–231.

——— and *P. MALANOTTE-RIZZOLI, 1989: Assimilation of altimeter data into an ocean circulation model: Space versus time resolution studies. *J. Phys. Oceanogr. 19,* 1507–1534.

JAKOB, R., and J.J. HACK, 1989: Parallel MIMD programming for global models of atmospheric flow. In *Proc. Supercomputing '89 Conference,* Reno, Nev., 13–17 November 1989, Association of Computing Machinery, New York, N.Y., 106–112.

KATZ, R.W., and *A.H. MURPHY, 1990: Quality/value relationships for imperfect weather forecasts in a prototype multistage decision-making model. *J. Forecasting 9,* 75–86.

KIEHL, J.T., and *V. RAMANATHAN, 1990: Comparison of cloud forcing derived from the Earth Radiation Budget Experiment with that simulated by the NCAR Community Climate Model. *J. Geophys. Res. 95,* 11679–11698.

*KILADIS, G.N., *H.VON STORCH, and H. VAN LOON, 1989: On the origin of the South Pacific Convergence Zone. *J. Climate 2,* 1185–1195.

*KO, S.D., J.J. TRIBBIA, and *J.P. BOYD, 1989: Energetics analysis of a multilevel global spectral model. Part I: Balanced energy and transient energy. *Mon. Weather Rev. 117,* 1941–1953.

*———, ———, and *———1989: Energetics analysis of a multilevel global spectral model. Part II: Kinetic energy, available potential energy, and total energy. *Mon. Weather Rev. 117,* 1954–1964.

*KUTZBACH, J.E., *P.J. GUETTER, and W.M. WASHINGTON, 1990: Simulated circulation of an idealized ocean for Pangaean time. *Paleoceanogr. 5*, 299–317.

*LABITZKE, K., and H. VAN LOON, 1989: The Southern Oscillation. Part IX: The influence of volcanic eruptions on the Southern Oscillation in the stratosphere. *J. Climate 2*, 1223–1226.

*____ and ____, 1990: Associations between the 11-year solar cycle, the quasi-biennial oscillation and the atmosphere: A summary of recent work. *Phil. Trans. R. Soc. Lond. A 330*, 577–589.

*____ and ____, 1990: The 11-year solar cycle in the stratosphere in the northern summer. *Ann. Geophys. 7*, 595–597.

*____ and ____, 1990: Sonnenflecken und Wetter-Gibt es doch einen Zusammenhang? *Die Geowissenschaften 8*, 1–6.

*____ and ____, 1990: The state of the atmosphere on the Northern Hemisphere at solar maximum, 1989–1990. *Belage z. Berl. Wetterk. 45(90)*, 1–12.

MADDEN, R.A., 1989: Summary of the Seventh Conference on Meteorology of the Middle Atmosphere. *Bull. Am. Meteorol. Soc. 70*, 1553–1559.

McWILLIAMS, J.C., 1990: A demonstration of the suppression of turbulent cascades by coherent vortices in two-dimensional turbulence. *Phys. Fluids A 2*, 547–552.

____, N.J. NORTON, P.R. GENT, and *D.B. HAIDVOGEL, 1990: A linear balance model of wind-driven, mid-latitude ocean circulation. *J. Phys. Oceanogr. 20*, 1349–1378.

MEEHL, G.A., 1989: The coupled ocean-atmosphere modeling problem in the tropical Pacific and Asian monsoon regions. *J. Climate 2*, 1146–1163.

____, 1990: Seasonal cycle forcing of El Niño in a global coupled ocean-atmosphere climate model. *J. Climate 3*, 72–98.

____ and W.M. WASHINGTON, 1990: CO_2 climate sensitivity and snow-sea-ice albedo parameterization in an atmospheric GCM coupled to a mixed-layer ocean model. *Clim. Change 16*, 283–306.

____, 1990: Water, electricity, and institutional innovation. In *Climate Change and U.S. Water Resources* (P. Waggoner, Ed.), Wiley, New York, N.Y., 367–393.

MIZZI, A.P., and A. KASAHARA, 1989: Intercomparison of daily variations of atmospheric variables, including diabatic heating rates, from the ECMWF, GFDL and GLA FGGE Level IIIb analyses. *J. Geophys. Res. 94*, 14717–14748.

*MULLEN, S.L., and D.P. BAUMHEFNER, 1989: The impact of initial condition uncertainty on numerical simulations of large-scale explosive cyclogenesis. *Mon. Weather Rev. 117*, 2800–2821.

*MURPHY, A.H., B.G. BROWN, and *Y.-S. CHEN, 1989: Diagnostic verification of temperature forecasts. *Weather and Forecasting 4*, 485–501.

NEWTON, C.W., 1990: Erik Palmén's contributions to the development of cyclone concepts, 1–18. In *Extratropical Cyclones* (C.W. Newton and E.O. Holopainen, Eds.), American Meteorological Society, Boston, Mass., 262 pp.

POLLARD, D., *I. MUSZYNSKI, S.H. SCHNEIDER, and S.L. THOMPSON, 1990: Asynchronous coupling of ice-sheet and atmospheric forcing models. *Ann. Glaciology 14*, 247–251.

PRICE, M.F., 1989: Global change: Defining the ill-defined. *Environment 31*, 18–20, 42–44.

____, 1990: The development of legislation and policies for Colorado's national forests. *Eth-Zürich Forstwissenschaftliche Beiträge 10*, 281–299.

____, 1990: Temperate mountain forests: Common-pool resources with changing, multiple outputs for changing communities. *Natural Resources J. 30*, 685–707.

____, 1990: Are mountain tourism and forestry inextricably linked? A discussion with examples from the Swiss Alps. In *Social Science in Natural Resource Recreation Management* (J. Vining, Ed.), Westview Press, Boulder, Colo., 201–218.

RANDEL, W.J., and D.L. WILLIAMSON, 1990: A comparison of the climate simulated by the NCAR Community Climate Model with ECMWF analyses. *J. Climate 3*, 608–633.

RASCH, P.J., and D.L. WILLIAMSON, 1990: On shape-preserving interpolation and semi-Lagrangian transport. *SIAM J. Sci. Stat. Comput. 11*, 656–687.

____ and ____, 1990: Computational aspects of moisture transport in global models of the atmosphere. *Q.J.R. Meteorol. Soc. 116*, 1071–1090.

ROBLE, R.G., and R.E. DICKINSON, 1989: How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophys. Res. Lett. 16*, 1441–1444.

*SALBY, M.L., R.R. GARCIA, *D. O'SULLIVAN, and J.J. TRIBBIA, 1990: Global transport calculations with an equivalent barotropic system. *J. Atmos. Sci. 47*, 188–214.

SCHNEIDER, S.H., 1989: Global climate and trace gas composition: From atmospheric history to the next century. In *Report of the Dahlem Workshop on Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere* (M.O. Andreae and D.S. Schimel, Eds.), Berlin, Germany, 19–24 February 1989, John Wiley and Sons, Chichester, England, 281–290.

——, 1990: The global warming debate heats up: An analysis and perspective. *Bull. Am. Meteorol. Soc. 71*, 1292–1304.

——, 1990: The science of climate-modelling and a perspective on the global-warming debate. In *Global Warming—The Greenpeace Report* (J. Leggett, Ed.), Oxford University Press, New York, N.Y., 44–67.

——, 1990: The costs of cutting - or not cutting - greenhouse-gas emissions. In *Global Warming—The Greenpeace Report* (J. Leggett, Ed.), Oxford University Press, New York, N.Y., 185–192.

*SEMTNER, A.J., and R.M. CHERVIN, 1990: Environmental effects on acoustic measures of global ocean warming. *J. Geophys. Res. 95*, 12973–12982.

SLINGO, A., 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature 343*, 49–51.

SPALL, M.A., 1990: Circulation in the Canary Basin: A model/data analysis. *J. Geophys. Res. 95*, 9611–9628.

*TREGUIER, A.M., and J.C. McWILLIAMS, 1990: Topographic influences on wind-driven, stratified flow in a β-plane channel: An idealized model of the Antarctic Circumpolar Current. *J. Phys. Oceanogr. 20*, 324–343.

TRENBERTH, K.E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Am. Meteorol. Soc. 71*, 988–993.

—— and J.G. OLSON, 1989: Temperature trends at the South Pole and McMurdo Sound. *J. Climate 2*, 1172–1182.

——, W.G. LARGE, and J.G. OLSON, 1989: The effective drag coefficient for evaluating wind stress over the oceans. *J. Climate 2*, 1507–1516.

*VAGLE, S., W.G. LARGE, and *D.M. FARMER, 1990: An evaluation of the WOTAN technique of inferring oceanic winds from underwater ambient sound. *J. Atmos. Oceanic Technol. 7*, 576–595.

VAN LOON, H., and *K. LABITZKE, 1990: Association between the 11-year solar cycle and the atmosphere. Part IV: The stratosphere, not grouped by the phase of the QBO. *J. Climate 3*, 827–837.

*VERRON, J., *E.J. HOPFINGER, and J.C. McWILLIAMS, 1990: Initial conditions in the merging of two-layer baroclinic vortices. *Physics Fluids A 2*, 886–889.

VUKICEVIC, T., and R.M. ERRICO, 1990: The influence of artificial and physical factors upon predictability estimates using a complex limited-area model. *Mon. Weather Rev. 118*, 1460–1482.

WASHINGTON, W.M., 1990: Where's the heat? *Nat. Hist.*, March 1990, 66–72.

—— and T.W. BETTGE, 1990: Computer simulation of the greenhouse effect. *Computers in Physics 4*, 240–246.

—— and G.A. MEEHL, 1989: Climate sensitivity due to increased CO_2: Experiments with a coupled atmosphere and ocean general circulation model. *Clim. Dynamics 4*, 1–38.

——, T.W. BETTGE, G.A. MEEHL, and *J.B. YOST, 1990: Computer simulation of the global climatic effects of increased greenhouse gases. *Int. J. Supercomputer Applications 4*, 5–19.

WEISS, J.B., and *E. KNOBLOCH, 1990: A stochastic return map for stochastic differential equations. *J. Stat. Phys. 58*, 863.

*WHITE, W.B., *C.K. TAI, and W.R. HOLLAND, 1990: Continuous assimilation of simulated GEOSAT altimetric sea level observations into a synoptic numerical ocean model of the California Current. *J. Geophys. Res. 95*, 3127–3148.

*——, *——, and ——, 1990: Continuous assimilation of simulated GEOSAT altimetric sea level into an eddy-resolving numerical ocean model: Part I: Sea level differences. *J. Geophys. Res. 95*, 3219–3234.

*____, *____, and ____, 1990: Continuous assimilation of simulated GEOSAT altimetric sea level into an eddy-resolving numerical ocean model: Part II: Referenced sea level differences. *J. Geophys. Res. 95,* 3235–3251.

WILLIAMSON, D.L., 1990: Semi-Lagrangian moisture transport in the NMC spectral model. *Tellus 42A,* 413–428.

*XUE, Y., *K.-N. LIOU, and A. KASAHARA, 1990: Investigation of the biogeophysical feedback on the African climate using a two-dimensional model. *J. Climate 3,* 337–352.

Other Publications

BAUMHEFNER, D.P., 1990: Prediction of forecast skill using Monte Carlo ensembles of 30-day forecasts. In *Proc. 14th Climate Diagnostics Workshop,* Scripps Institution of Oceanography, La Jolla, Calif., 16–20 October 1989, Climate Analysis Center, National Weather Service, NOAA, Washington, D.C., 339–343.

BRANSTATOR, G., 1990: Anomalous forcing of the atmosphere in the presence of weak and strong stationary waves. *Papers Presented at the First BMRC Modelling Workshop,* Melbourne, Australia, 11–12 July 1989 (J.D. Jasper, Ed.), Research Report No. 21, 64–71.

BRASSEUR, G., Coordinator, et al., including B.A. BOVILLE, R. GARCIA, and S. MADRONICH, 1990: Theoretical predictions, Chapter 3 in *Scientific Assessment of Stratospheric Ozone: 1989,* Global Ozone Research and Monitoring Project, Report No. 20, Vol. 1, World Meteorological Organization, Geneva, Switzerland, 283–396.

BUJA, L.E., *J. PAEGLE, and D.P. BAUMHEFNER, 1990: The sensitivity of the high-latitude response to tropical heating anomalies in real-data extended range forecasts. In *Proc. 14th Climate Diagnostics Workshop,* Scripps Institution of Oceanography, La Jolla, Calif., 16–20 October 1989, Climate Analysis Center, National Weather Service, NOAA, Washington, D.C., A-7–A-12.

CHERVIN, R.M. and *A.J. SEMTNER, 1990: An ocean modeling system for supercomputer architectures of the 1990s. In *Climate-Ocean Interaction* (M.E. Schlesinger, Ed.), Kluwer Academic Publishers, Dordrecht, The Netherlands, 87–95.

DICKINSON, R.E., 1989: Predicting climate effects. *Nature 342,* 343–344.

ERRICO, R.M., 1989: *Theory and Application of Nonlinear Normal Mode Initialization.* Technical Note NCAR/TN-344+IA, NCAR, Boulder, Colo., 145 pp.

GENT, P.R., 1989: Balanced models for ocean circulation studies. In *INO Symposium on Global Ocean Prediction Systems,* Princeton, N.J., 11–13 May 1988, INO Report 89-6, Stennis Space Center, Miss., 33–34.

____, 1990: A new ocean GCM for tropical ocean and ENSO studies. In *Proc. Western Pacific International Meeting and Workshop on TOGA-COARE* (J. Picaut, R. Lukas, and T. Delcroix, Eds.), Nouméa, New Caledonia, 24–30 May 1989, Centre Orstom de Nouméa, 445–450.

GLANTZ, M.H., 1990: *On Assessing Winners and Losers in the Context of Global Warming.* Report of the Workshop, St. Julians, Malta, 18–21 June 1990, United Nations Environment Program, Environmental and Societal Impacts Group publication, NCAR, Boulder, Colo., 44 pp.

____ and L.E. FEINGOLD, Eds., 1990: *Climate Variability, Climate Change and Fisheries.* Environmental and Societal Impacts Group/National Marine Fisheries Service, Environmental Protection Agency Study, Boulder, Colo., 139 pp.

KASAHARA, A., A.P. MIZZI, and *L.J. DONNER, 1990: Impact of cumulus initialization upon the spin-up of precipitation forecasts in the tropics. In *Proc. International Symposium on Assimilation of Observations in Meteorology and Oceanography,* Clermont-Ferrand, France, 9–13 July 1990, World Meteorological Organization, Geneva, Switzerland, 221–224.

MEARNS, L.O., 1989: Climate variability. In *Report to Congress on the Potential Effects of Global Climate Change on the U.S.,* Environmental Protection Agency, Washington, D.C., EPA-230-05-89-050, 27–55.

____, 1990: Future directions in climate modeling. A climate impacts perspective. In *Climate Change: Implications for Water and Ecological Resources* (G. Wall and M. Sanderson, Eds.), *Proc. International Symposium/Workshop,* Department of Geography, University of Waterloo, Ontario, Canada, 51–58.

____, 1990: Book review of *Recent Climate Change: A Regional Approach. The Environmental Professional 11,* 456–457.

——, S.H. SCHNEIDER, and *P.H. GLEICK, 1990: Climate forecasting. In *Climate and Water: Climate Change, Climatic Variability, and the Planning and Management of U.S. Water Resources*, American Association for the Advancement of Science, Wiley Press, New York, N.Y., Chapter 6, 87–137.

MEEHL, G.A., 1990: ENSO and CO_2 climate change in a coupled ocean-atmosphere GCM. In *Proc. 14th Climate Diagnostics Workshop*, Scripps Institution of Oceanography, La Jolla, Calif., 16–20 October 1989, Climate Analysis Center, National Weather Service, NOAA, Washington, D.C., 41–46.

MILLER, K.A., 1989: Book review of *Assessing the Social Implications of Climate Fluctuations: A Guide to Climate Impact Studies*, by W.E. Riebsame. *Clim. Change 16*, 149.

*MULLEN, S.L., and D.P. BAUMHEFNER, 1989: Monte Carlo simulations of large-scale explosive cyclogenesis. In *Proc. 12th Conference Weather Analysis Forecasting*, Monterey, Calif., 2–6 October 1989, American Meteorological Society, Boston, Mass., 343–346.

PRICE, M.F., 1990: *The Human Aspects of Global Change*. Funded by Climate Dynamics Program, Division of Atmospheric Sciences, NSF, Washington, D.C. Available from Environmental and Societal Impacts Group, NCAR, Boulder, Colo., 80 pp.

——, 1990: Book review of *The Himalayan Dilemma: Reconciling Development and Conservation*, by J.D. Ives and B. Messerli. *Land Use Policy 7*, 93–94.

——, 1990: Defining global change. Letter in *Environment 32*, 42.

SCHNEIDER, S.H., 1989: News plays fast and loose with the facts. *Detroit News*, 5 December, 10A.

——, 1990: The changing climate. Reprinted in *Managing Planet Earth*, Readings from *Scientific American*, W.H. Freeman and Company, New York, N.Y., 25–36.

——, 1990: The changing climate: A risky planetwide experiment. In *Greenhouse Glasnost The Crisis of Global Warming* (T.J. Minger, Ed.), The Ecco Press, Institute for Resource Management, New York, N.Y., 117–131.

——, 1990: The global warming debate: Science or politics? *Environmental Science and Technology 24*, 432–435.

——, 1990: The changing climate. *J. Japan Soc. Civil Engineering 75*, 50–55, adapted from *Scientific American.*

——, 1990: Debating gaia. *Environment 32*, 29–32.

——, 1990: Cooling it. *World Monitor 3*, 30–38.

——, 1990: Statement before the Parliamentary Forum on Global Change, Ottawa, Canada, (H. Brightwell, Chairman), 23–24 April 1990, Canadian Government Publishing Center, Ottawa, Canada, 33–47.

——, *P.H. GLEICK, and L.O. MEARNS, 1990: Prospects for climate change. In *Climate and Water: Climate Change, Climatic Variability, and the Planning and Management of U.S. Water Resources*, American Association for the Advancement of Science, Wiley Press, New York, N.Y., Chapter 3, 41–73.

SHEA, D.J., and R.A. MADDEN, 1990: Potential for long-range predictability of monthly mean surface temperatures over North America. *Proc. 14th Climate Diagnostics Workshop*, Scripps Institution of Oceanography, La Jolla, Calif., 16–20 October 1989, Climate Analysis Center, National Weather Service, NOAA, Washington, D.C., 344–349.

THOMPSON, P.D., 1990: Charney and the revival of numerical weather prediction. In *The Atmosphere—A Challenge: The Science of Jule Charney* (R.S. Lindzen, E.N. Lorenz, and G.W. Platzman, Eds.), American Meteorological Society, Boston, Mass., 93–119.

TRENBERTH, K.E., 1990: Operational data for CCM validation. In *CCM Progress Report—July 1990*, Technical Note NCAR/TN-351+PPR (D.L. Williamson, Ed.), NCAR, Boulder, Colo., 70–71.

——, 1990: Recent observed interdecadal climate changes. In *Proc. AMS Special Session on Climate Variations and Joint Session on Hydrology and Climate Variations*, Anaheim, Calif., 4–9 February 1990, American Meteorological Society, Boston, Mass., 91–95.

—— and G.W. BRANSTATOR, 1989: Global circulation anomalies during 1988. In *Proc. Third International Conference on Southern Hemisphere Meteorology and Oceanography*, Buenos Aires, Argentina, 12–17 November 1989, American Meteorological Society, Boston, Mass., 110–115.

——, ——, and *P.A. ARKIN, 1989: Origin of the 1988 North American drought: The drought of

1988 and beyond. In *Proc. Strategic Planning Seminar*, co-sponsored with the National Academy of Sciences and Resources for the Future, 18 October 1988, Washington, D.C., U.S. Department of Commerce, NOAA, National Climate Program Office, Washington, D.C., 129–141.

____, D.J. SHEA, and *R.W. REYNOLDS, 1990: A new sea surface temperature climatology. In *CCM Progress Report—July 1990,* Technical Note NCAR/TN-351+PPR (D.L. Williamson, Ed.), NCAR, Boulder, Colo., 72.

TRIBBIA, J.J., 1991: The rudimentary theory of atmospheric teleconnections associated with ENSO. In *ENSO Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact* (M.H. Glantz, R.W. Katz, and N. Nicholls, Eds.), Cambridge Press, Cambridge, England, 285–308.

*VON STORCH, H., and D.P. BAUMHEFNER, 1989: An index of the tropical 30–60 day wave and its prediction. *Research Activities in Atmospheric and Oceanic Modeling,* Climate Analysis Center/Joint Scientific Committee Working Group on Numerical Experimentation, Report No. 13, World Meteorological Organisation, Geneva, Switzerland, 6.38–6.41.

*____ and ____, 1990: *Principal Oscillation Pattern Analysis of the Tropical 30- to 60-Day Oscillation. Part II: The Prediction of Equatorial Velocity Potential and Its Skill.* Max Planck Institute for Meteorology, Report No. 53, Hamburg, Germany, 39 pp.

WILLIAMSON, D.L., Ed., 1990: *CCM Progress Report—July 1990.* Technical Note NCAR/TN-351+PPR, NCAR, Boulder, Colo., 108 pp.

* An asterisk denotes a non-NCAR author.

High Altitude Observatory

The research goal of the High Altitude Observatory (HAO) is to understand the sun as a physical system. Although there is an astrophysical component in HAO's research, the primary interest is the physical processes that govern the sun, the interplanetary medium, and the earth's upper atmosphere as an integral system.

The sun's magnetic field makes it a variable star. The combined action of convection and rotation generates the solar magnetic field in cycles of approximately 22 years. This magnetic field alters the outward flow of energy—directly, by transforming fluid energy into magnetic energy and by providing additional modes of energy transport to the outer layers, and indirectly, by altering both the convective and the radiative transport efficiencies. In the solar atmosphere, the magnetic fields control the thermal and dynamic properties of plasmas that, in turn, give rise to the wealth of physical phenomena associated with the variable outputs of the sun in radiation, particles, and magnetic fields. Understanding the physics of these phenomena is both intellectually challenging and essential to our desire to be able to predict solar variability.

The sun is the principal forcing agent of the terrestrial environment. The different degrees of variability across the spectrum of solar radiation and the coupling of the earth's upper atmosphere with a variable interplanetary medium have direct as well as catalytic influences on the terrestrial environment that we have not yet understood. Yet understanding these influences is crucial to our ability to separate anthropogenic from natural causes in society's current concern about global change. The study of the sun and its physical effects on the earth's upper atmosphere, pursued as a broad scientific program at HAO, lays the foundation for the eventual application of our knowledge to such areas as the global change.

In two sections of HAO there is also significant work on problems of stellar physics analogous to the solar topics emphasized. The unusual breadth of the program strains the available resources but is necessary for a coherent approach to the understanding of solar variability and its consequences. Fortunately, the unifying theme of solar variability produces strongly overlapping interests in the three sections and leads to a healthy level of interaction and cooperation.

Although HAO operated with four scientific sections last year, at year's end the Solar Interior Section and Solar Activity and Magnetic Fields Section were combined into the new Solar Interior and Lower Atmosphere Section. Thus this report is written from the perspective of three scientific sections, while staff are still listed in four.

Significant Accomplishments

Some highlights of the year's research activities are described below.

- In 1985, Boon Chye Low derived a class of analytic solutions describing magnetostatic atmospheres with variations in all three spatial coordinates. These solutions raised the possibility of modeling long-lived (hence quasi-static) features of the corona with a new degree of geometric realism. In a new treatment of the governing equations, Low has generalized these solutions to a broader set of equilibrium states in which the electric current density is allowed to have a component along the magnetic field. These analytic solutions offer the opportunity of modeling the atmosphere over a complex solar active region, which is intrinsically three-dimensional and beyond the reach of older models with geometric symmetries.

- Richard Steinolfson (visitor, Southwest Research Institute) in his studies of mass ejection initiation and of the propagation of magnetohydrodynamic shock waves ahead of mass ejection using the SMM database, has performed a numerical simulation of the slow evolution of a coronal helmet streamer produced by a gradual shear of the closed magnetic field lines. This evolution leads to the dynamical eruption of the streamer when the accumulated shear becomes large enough. Individual closed fields follow a trajectory in this process that is qualitatively like those in events followed by HAO's Mauna Loa Solar Observatory (MLSO) and Solar Maximum Mission satellite (SMM) instruments—a long period of slow outward extension followed by a rapid acceleration and escape from the sun. This simulation was carried out for an axially symmetric coronal helmet streamer that included a flow of solar wind on open field lines but without introduction of a coronal cavity within the helmet streamer belt. It gives significant support to earlier ideas that mass ejections occur when a large-scale, closed coronal structure evolves to a point where it can no longer remain in quasi-static equilibrium.

- Keith MacGregor and Paul Cohen (summer undergraduate student, Yale University) have extended a previously developed parameterized description of internal angular momentum transport, together with a direct computation of the rate of angular momentum removal by a magnetically coupled stellar wind, to trace the rotational evolution of solar-type stars. The new model contains explicit treatment of the reapportionment of angular momentum between the radiative and convective regions occurring during contraction to the main sequence.

- The promise of a dramatic increase in angular resolution for Stokes polarimetery, accompanied by unprecedented precision in the accuracy of the field measurements, was emphasized by results from an observing run carried out in May and June 1990 with the prototype advanced Stokes polarimeter. The instrument provided first observations of the vector magnetic field structure of a small sunspot with high angular resolution.

- Pawan Kumar, in collaboration with Edward Lu (visitor, Stanford University), investigated the location of the source of acoustic emission which excites high-frequency solar acoustic oscillations (frequency greater than approximately 5.5 mHz). Kumar and Lu showed that in contrast with the trapped solar acoustic oscillations (frequency less than about 5.5 mHz), the position of the peaks in the power spectrum for high-frequency oscillations is dependent on the source location. This was used to determine the source property, which was found to be located approximately 200 km below the visible photosphere. Since the source strength depends on the convective velocity, this investigation opened up a new probe of the upper part of the solar convection zone.

- Visitor Michael Thompson (now at Queen's College, London), in collaboration with Jorgen Christensen-Dalsgård (NCAR affiliate scientist, Århus University, Denmark) and Douglas Gough (Cambridge University), used existing solar p-mode frequencies to estimate the depth of the solar convection zone. This work was based on the sensitivity of p-mode frequencies to the variation of sound speed with depth in the solar envelope. At the bottom of the sun's convectively mixed zone, the temperature gradient goes abruptly from an adiabatic value to a superadiabatic one. The resulting change of slope in the sound speed vs. depth relation allows a sensitive measurement of the convective zone depth. The convection zone turns out to have a depth of 200 $\pm$ 1 Mm, with the uncertainty in this value arising mostly from uncertainties in the composition of the material in the solar envelope.

- The NCAR thermosphere/ionosphere general circulation model (TIGCM) has been extended to include a dynamo model to represent self-consistent electrodynamic interactions between the thermosphere and ionosphere. The dynamo model uses the ionospheric electrical conductivities and neutral winds calculated by the TIGCM and solves the dynamo equations using the real magnetic field and apex coordinates. The calculated global potential pattern specifies the ion drifts that are then used to determine the ionospheric structure and thermospheric ion drag at the next model time step. This new thermosphere/ionosphere/electrodynamics general circulation model couples the thermosphere and ionosphere in a self-consistent manner, and the model now only requires the specification of external forcings, such as the solar extreme ultraviolet (EUV) and UV fluxes, auroral particle precipitation, and the amplitudes and phases of the upward propagation semidiurnal tides.

Coronal/Interplanetary Physics Section

The long-range goals of the Coronal/Interplanetary Physics (CIP) section are to describe (observationally and theoretically) the physical properties of the solar corona and its interplanetary extension into the solar wind and to understand the physical processes that determine the state of this extended solar atmosphere as an integral physical system. Pursuit of these broad goals includes studies of the role of the large-scale solar magnetic field in coronal structures; specific relationships between phenomena in the solar wind, the corona, and the lower layers of the solar atmosphere; long-term variations in the coronal and solar wind characteristics; and effects of the solar wind upon the interplanetary/terrestrial environment. These studies lead to a substantial (and desirable) overlap in research and personnel with the other sections of the observatory. CIP's research program has encompassed observing projects that use both ground-based and spacecraft-borne instruments, interpretative studies using these and other observations, and a theoretical effort aimed at understanding basic coronal and interplanetary physical processes, as well as specific phenomena revealed by observations. The section's interests extend beyond the solar system to other space and astrophysical systems where similar phenomena may occur or similar physical processes may be important.

Coronal Magnetic Field

The magnetic field generated in the solar convection zone extends out into the solar corona, where it is sufficiently strong (the energy density in the field is about an order of magnitude greater than that in the plasma) to dominate coronal dynamics. Spatial inhomogeneities or temporal changes in the solar field, or flows of the coronal plasma, all produce electric currents in the corona and a magnetic force comparable to the two other major forces (solar gravity and the pressure gradient force) acting on the plasma. This effect gives rise to a rich variety of magnetically controlled structures; for slowly changing or quasi-steady conditions these structures range from magnetically open and closed regions with dimensions comparable to the size of the sun itself to a host of smaller-scale magnetic loops containing plasma in various thermodynamic states in the low corona and chromosphere. The hydromagnetic equilibrium of these structures, including the outward expansion of the solar wind along open magnetic field lines; the stability of any equilibrium state; and the onset of eruptions leading to time-dependent phenomena pose interesting questions that are pursued systematically in the CIP Section. While magnetohydrodynamic theory and modeling are an observatory-wide program, the dominance of magnetic effects in the corona and the observability and resolvability of coronal magnetic structures have led to a focus of this program on coronal problems.

In the low corona where solar wind expansion speeds are small, the quiescent state of the magnetized atmosphere can be approximated by a static equilibrium.

An ongoing program continues to expand our understanding of these magnetostatic equilibria to more complicated geometries. In 1985, Low derived a class of analytic solutions describing magnetostatic atmospheres with variations in all three spatial coordinates. These solutions raised the possibility of modeling long-lived (hence quasi-static) features of the corona with a new degree of geometric realism.

With Arthur Hundhausen and Richard Wolfson (Middlebury College), Low continues to explore the wide range of possible solutions encompassed by these models. Although the flow of solar wind is not explicitly part of these models, large-scale, open magnetic regions can be incorporated into them by a boundary condition that requires the field to be predominantly open at large distances from the sun. One of the goals of this effort is the generation of coronal models that can be compared with the actual appearance as seen in HAO's white-light coronal observations (described below). The insight and intuition built upon such comparisons should prove useful in the quantitative interpretation of these data.

The three-dimensional magnetostatic states derived in 1985 were based on the simplifying assumption that the electric currents (that generate the Lorentz force to confine and support the plasma flow) are everywhere perpendicular to gravity. Since the magnetic field in most models of interest has a component parallel to gravity, the field in these solutions has zero net twist. In a new treatment of the governing equations, Low has generalized these solutions to a broader set of equilibrium states in which the electric current density is allowed to have a component along the magnetic field. A particular subset of these equilibrium states can be constructed explicitly where the magnetic field is force-free (with a current parallel to and proportional to the magnetic field) in the upper part of the atmosphere but is anchored to the lower solar atmosphere in a boundary layer of finite thickness where electric currents flow across the magnetic field and the Lorentz force is balanced everywhere by pressure gradients and gravity. These analytic solutions offer the opportunity of modeling the atmosphere over a complex solar active region, which is intrinsically three-dimensional and beyond the reach of older models with geometric symmetries. Low continues to explore the properties of the new set of solutions and their solar applications.

The topology of a magnetic field in electrically conducting plasma is fixed by its evolutionary history under the "frozen-in" condition. In general, the preservation of the field topology requires the presence of electric current sheets if the field relaxes to an equilibrium state. Current sheet formation in the presence of magnetic neutral points has been known for decades dating back to works by Syrovatskii, Sweet, and others. More recently, Eugene Parker showed that electric current sheets can form under general astrophysical circumstances in the absence of magnetic neutral points. This process may set the stage for local magnetic reconnection and is attractive as a mechanism for coronal heating.

Low and Wolfson demonstrated in 1988 how electric current sheets may form in the absence of magnetic neutral points as the result of displacement of the magnetic footpoints at the boundary of the atmosphere taken to be rigid, using a simple two dimensional force-free magnetic field in the infinite half space above a plane. Recently, the result of Low and Wolfson was criticized by Judith Karpen, Spiro Antiochos, and Rick DeVore (all at U.S. National Research Laboratory). Based on an (incorrect) interpretation of the Lorentz forces associated with electric current sheets and a numerical simulation, these authors claimed that the result of Low and Wolfson depended on the use of a rigid boundary to the extent that if the boundary were of a finite thickness and not rigid, no current sheets would form. Low has constructed new magnetostatic solutions to show that the conclusions of these authors are not valid. The new solutions show that the formation of electric current may be modified near the lower boundary but is not suppressed by relaxing the rigid boundary condition. With this analytical demonstration, Low offered plausible explanations for the null numerical result of these authors and suggestions for future numerical simulations to study this process.

The application of these analytic hydromagnetic models to solar and stellar coronas will ultimately require incorporation of an outward flow from open magnetic regions. The collaboration between You Qiu Hu (University of Science and Technology of China, Beijing) and Low continues on the analytical construction of an axisymmetric hydromagnetic wind flowing from the two polar regions of a star sandwiching an equatorial belt of static closed magnetic fields. In 1988 Hu and Low showed that this may be accomplished by the reduction of the steady hydromagnetic equations to ordinary differential equations starting with a simple form for the magnetic field in the flow region. The goal is to produce a model with the following qualitative physical features: the polar wind is monotonically accelerated with increasing distance but is nearly static close to the surface of the star, the density at fixed radial distance decreases towards the pole, and there is force balance between the wind and the equatorial static region.

Coronal Observations

The HAO tradition of coronal observations continued in 1990 with the operation of the Mark III coronameter and the Hα prominence monitor at MLSO in Hawaii. The almost continuous coverage of the corona since 1980 with these instruments and with the coronagraph on the SMM spacecraft until its demise in December 1989 provided an unprecedented view of coronal evolution and activity during the ascending phase of a solar activity cycle. In fact, a decline in smoothed sunspot numbers and in flare counts since mid-1989 gives a preliminary suggestion that the 1980–89 epoch of joint MLSO and SMM observations spanned the entire period from minimum to maximum of the present activity cycle. HAO continues detailed analysis of the evolution of the large-scale coronal features from their minimum state—large coronal holes (or open magnetic regions) near both poles of the sun, separated by a belt of coronal streamers (closed magnetic regions) near the solar equator—to their maximum state—smaller holes and individual streamers occurring almost randomly around the sun. A remarkable increase in coronal activity, as epitomized by the phenomenon of coronal mass ejections, has provided the opportunity to study the origin of this activity and its relationship to the slow evolution of coronal structures (and magnetic fields) as never before.

With the end of useful data transmission from the SMM satellite in mid-November 1989, Hundhausen and colleagues have focused their attention on the systematic analysis of the remarkable data set obtained during the 1980 and 1984–89 epoch of observations. Maps of the quiet structure of the corona have been constructed for this entire epoch and, along with similar maps of the lower corona from the MLSO coronameter, provide a synopsis of this structure and its evolution at heights ranging from 0.2 to 4 solar radii above the base of the corona. Over 1300 coronal mass ejections have been identified in the SMM data, with 500 in the 10 1/2 months of observation from 1989. The basic properties—location, size, and ejection speed—of these events have been measured (where possible), leaving estimates of masses and energies as the remaining properties awaiting systematic analysis. The large number of mass ejections seen as solar activity approached its maximum level in 1989 also led to many more examples of events observed in the low corona (0.2 to 1 solar radii above its base) from MLSO and the outer corona (0.6 to 4 solar radii above its base) from SMM. These joint observations provide a far more complete history of mass ejection formation then previously available and can be used to sharpen our view of the physical origins of this phenomenon. Some of the results obtained to date and HAO's attacks on unanswered questions (both old and new) are described below.

With the refurbishment of the Mark III coronameter at MLSO essentially complete (work continues on a microprocessor), David Sime and Jack Streete (visitor, Rhodes College) have focused on preparations for the 1991 eclipse. Their major scientific goal for this eclipse is to obtain carefully calibrated measurements of the coronal brightness and polarization from the MLSO site and to use these measurements to improve the calibration of the polarization brightness measurements made with the Mark III coronameter. A small grant was obtained from NASA to assist in upgrading the Mark III instrument to support the ULYSSES measurements (scheduled for 1995) of interplanetary conditions over the poles of the sun. The major components of the upgrade effort (by Richard Fisher and Sime) involve the outward extension of the field of view to better define the coronal/interplanetary current sheet location and detect coronal mass ejections, and replacement of the present data storage system with one using Exabyte tapes to smooth out the transfer, archiving, and viewing of these data.

Work (led by Fisher) continues on preparation of the SPARTAN 201 white-light coronagraph for deployment by the space shuttle. After the extensive testing of the HAO instrument described in the last annual report, an integration into the 1300 kg subsatellite system was carried out at the NASA Goddard Space Flight Center (GSFC). Alignment and vibrational tests were carried out with the companion Smithsonian Astrophysical Observatory ultraviolet instrument. The instrument was found to be ready for flight operations and since sent back to HAO for continued internal tests, including calibrations and determination of stray light characteristics. A launch date of October 1992 is now favored by NASA project management; final integration and a 40-h test period will complete the preflight phase of this project.

Coronal Properties and Physical Processes

The traditional white-light coronal observations utilize the photospheric light that has been Thomson-scattered by electrons in the corona. These observations thus yield fairly direct information on the electron density structure and its variations on the slow or evolutionary time scale and the short or dynamic time scale. However, white-light observations yield no direct information on other coronal properties of equal intrinsic importance; inference of solar wind flows or coronal temperatures requires careful use of other observations in conjunction with the white-light measurements. The SPARTAN 201 program described above is intended to provide one set of coordinated observations that can lead to flow and temperature measurements.

Edward Shoub, Thomas Holzer, and Egil Leer (NCAR affiliate scientist, Institute for Theoretical Astrophysics, Oslo, Norway) have developed solar wind models crucial to the interpretation of such observations. Their model includes both ionized hydrogen and helium in an expanding corona; it is thus a three-fluid model (protons, electrons, and alpha particles). They have shown that a sufficient abundance of the alpha particles near the base of the corona has a profound and desirable influence on the solar wind. It diminishes the extreme sensitivity of the solar wind mass flux to the coronal temperature—a sensitivity that in conventional, two-fluid models makes it very hard to understand why the mass flux in the solar wind is not observed to undergo wild fluctuations. Shoub has developed spectroscopic diagnostics for helium in the solar wind, predicting the flux and line profile for He II, 304 Å photons in relation to the flux scattered by H I (in the Lα line). These processes can have an important impact on the interpretation of the SPARTAN observations in terms of the solar wind speed at different heights in the corona.

Fisher, in collaboration with Frank Orrall (University of Hawaii), Madhulika Guhathakurta, and Gary Rottman (both of University of Colorado), has combined images of the 17 March 1988 eclipse obtained in white light, in the 5303 Å line of Fe XIV, and in 170 Å X-rays to study the temperature structure of the solar corona. Synoptic images of the corona obtained by the Mark III instrument at MLSO during the weeks before and after the eclipse provide information on the location and extent of the large-scale coronal features. Comparison of these images indicates that the highest coronal temperatures occurred in or near coronal streamers, at the boundary between the polar magnetic fields remaining from the previous activity cycle and the high-latitude fields of opposite magnetic polarity from the new activity cycle.

Coronal Mass Ejections

As mentioned above, the frequency of coronal mass ejections increased tremendously during the 1986–89 epoch of rising solar activity; 53, 114, 377, and 500 mass ejections have been identified thus far in SMM coronagraph observations from the years 1986, 1987, 1988, and 1989 respectively. Although a careful duty-cycle correction is necessary to convert these numbers into accurate frequencies (or rates of occurrence), an order of magnitude variation from minimum to maximum activity is evident. It is also clear that mass ejections in 1989 occurred as frequently as or more frequently than during the original solar maximum observing period (of several months) in 1980. The duty-cycle corrected rates for both 1980 and 1989 are just above two ejections observed per 24-hour day.

The systematic measurement of basic properties of mass ejections reveals an interesting pattern of variations over the entire period of SMM observations. For example, the spatial locations of the ejections change in consort with activity and with the structure of the quiet corona. Mass ejections were observed over a wide range of solar latitudes during the 1980 period of high solar activity, became confined to the equatorial regions as activity declined to its minimum level from 1984 to 1986, and once again spread to cover a wide range of solar latitudes during the 1986–89 period of rising activity. The latter epoch is of special interest in testing statistically the relationship of mass ejections to other forms of solar activity and to magnetic fields of different spatial scales. As the distribution of mass ejections spread to high latitudes, the small-scale magnetic fields in active regions and the solar flares that represent temporal disturbances of those fields displayed their expected evolution to low latitudes. However, solar prominences and large-scale bright structures in the corona, features associated with larger-scale magnetic fields, spread poleward in a manner similar to that of the mass ejections. These patterns are consistent with suggestions that mass ejections are related to the evolution of large-scale magnetic fields and are not caused by the familiar eruptions of smaller-scale fields marked by solar flares. We find no significant changes in the angular dimensions of mass ejections over the activity cycle or with the spread to high latitudes; preliminary results from 1989 show no significant differences in the speeds of high-latitude and low-latitude mass ejections.

The plethora of mass ejections observed in 1988 and 1989 permits a far more extensive examination of the origins of this phenomenon on a event-by-event basis.

Of particular interest is the causal relationship between mass ejections and solar flares, as observed in the X-ray emission believed to reflect the energy deposition (hard X-rays) and accumulated heating (soft X-rays) of coronal plasma by the flare mechanism. In several mass ejections observed both by the MLSO coronameter and the SMM coronagraph, the actual onset of the eruption can be determined (with no extrapolation into an unobserved region of the corona) to an uncertainty of only a few minutes. Hundhausen and Sime have found several such events related to major X-ray flares that clearly demonstrate onset of flare emission after the mass ejection has been accelerated outward. No clear examples have been found where a simple X-ray flare precedes the mass ejection. These continuing studies give strong support to a similar result observed in several less accurate comparisons made in the past several years. Hundhausen and Sime again suggest that the magnetic reconnection thought to produce solar flares occurs after, and may be a consequence of, the large-scale eruption of magnetic fields that they see as a coronal mass ejection.

These results are largely consistent with a model of magnetic reconnection proposed by Roger Kopp and Gerald Pneuman on the basis of Skylab observations in the 1970s but largely superseded in the 1980s by models of flares and magnetic reconnection as the drivers of mass ejection. However, other well-observed mass ejections raise serious questions as to the generality of the Kopp and Pneuman model. Hundhausen and Chrisopher St. Cyr have found many bright and fast mass ejections involve soft X-ray emission that is very weak or even undetectable above the background emission of the sun. Some of these events contain prominences that erupted from the limb or even the visible disk of the sun; any X-ray emission related to these ejections cannot be hidden behind the sun. The events studied to date exhibit a variation in the intensity of X-ray emission of two to three orders of magnitude for ejections with comparable speed. Most of the X-ray "poor" mass ejections studied thus far occurred at high solar latitudes and involved the eruption of large quiescent prominences, as described in the previous annual report. Such a huge variability in X-ray emission raises serious questions as to the existence of any essential physical connection between the mass ejection and X-ray flare phenomena. CIP continues the study of additional events and the comparison of masses and energies of ejections with associated X-ray intensities in order to evaluate the validity of the present conclusions.

Steinolfson has continued his studies of mass ejection initiation and of the propagation of magnetohydrodynamic (MHD) shock waves ahead of mass ejection. He has performed a numerical simulation of the slow evolution of a coronal helmet streamer produced by a gradual shear of the closed magnetic field lines. This evolution leads to the dynamical eruption of the streamer when the accumulated shear becomes large enough. Individual closed fields follow a trajectory in this process that is qualitatively like those in events followed by the MLSO and SMM instruments—a long period of slow outward extension followed by a rapid acceleration and escape from the sun. This simulation was carried out for an axially symmetric corona that included a flow of solar wind on open field lines but without introduction of a coronal cavity within the helmet streamer belt. It gives significant support to earlier ideas that mass ejections occur when a large-scale, closed coronal structure evolves to a point where it can no longer remain in quasi-static equilibrium.

Steinolfson and Hundhausen have continued their study of slow and intermediate shock formation and propagation in front of coronal mass ejections. The formation of flattened or concave-outward fronts for both of these "exotic" classes of shocks has been confirmed in simulations that start with a realistic coronal model. The resulting patterns of enhanced density (or brightness as seen by a white-light coronagraph) produced by the shock and the outward motion of the dense helmet streamer taken to be the site of the ejection correspond to the patterns seen in the SMM observations. A full parameter study and detailed comparisons with the observations are necessary before the existence of these shocks in coronal mass ejections can be substantiated.

Solar and Stellar Winds

Solar and stellar wind studies at HAO are conducted both in this section and in the Solar Activity and Magnetic Fields section. The research program centers on basic physical mechanisms important to the generation of the solar wind and the evolution of solar wind structure, with a particular interest in applying the physical insight gained in these studies to the theory of stellar winds. HAO participates, principally through Holzer, in several space experiments, already approved, to observe solar wind properties—SPARTAN, ULYSSES, and the International Solar Terrestrial Physics missions. These experiments hold prospects of resolving some of the outstanding issues concerning the acceleration region of the wind. Holzer, Shoub, Leer, and other collaborators are developing diagnostic tools for data interpretation.

The revisions of classical transport theory implied by Shoub's work on Coulomb collisions in a plasma (see the description in the Solar Interior and Lower Atmosphere section of this report) may also be important for understanding heat conduction in the solar wind. Shoub is engaged in a long-term study of this and other solar wind physical processes, with an immediate goal of finding whether a nonclassical heat conduction can explain the observed properties of high-speed solar wind. He is working on the numerical algorithms needed to solve the kinetic equations for the coronal expansion.

Sime, Victor Pizzo, and Michelle Abboud (summer undergraduate student from Fairfield University) have examined the radio scintillation signals produced by various types of solar wind disturbances, including a density enhancement near the equator of a "tilted dipole," the density enhancements produced by corotating high-speed streams in the same model, and a true time-dependent disturbance moving out through the solar wind. Under the conventional assumption that the radio scintillation signal (or index) is produced by electron density fluctuations that are in turn proportional to the electron density itself, they have identified two major problems with the conventional interpretation of the scintillation observations. The first problem concerns the observed amplitudes of scintillation enhancements that have been attributed to solar wind density structures—the observed amplitudes (relative to background) would demand much higher density enhancements than are actually observed in the solar wind. The second problem is that the changing patterns of scintillation enhancements produced by the three different solar wind disturbances mentioned above are so similar that it is questionable whether current observations could distinguish among them.

Pizzo has continued his studies of solar wind stream interactions. His numerical models can now deal with these interactions in three dimensions, and have been applied to the "tilted-dipole" geometries suggested by coronal observations. He has obtained a three-year NASA grant to apply the existing model to *Pioneer* observations of streams in the outer heliosphere and to continue improvements on the three-dimensional treatment of this problem.

One of the important effects of the expansion of the magnetized solar wind plasma throughout the solar system is on the population of cosmic rays and other particles entering that system. Bogdan, Martin Lee (University of New Hampshire), and Peter Schneider (Max Planck Institute for Physics and Astrophysics, Garching, Germany) have examined this process for ions that can be created in the wind through charge exchange or photo-ionization of interstellar or cometary neutrals. They have derived a set of coupled spatially homogeneous quasi-linear equations which describe the evolution of the energetic ion omnidirectional distribution function and the intensities of the MHD waves propagating parallel and antiparallel to the ambient magnetic field. Numerical solutions of these kinetic equations were performed for four cases of pickup ions in the solar wind that illustrate the essential features of the evolution of: (1) interstellar pickup helium near a heliocentric radius of 1 AU, (2) interstellar pickup hydrogen near 10 AU, (3) water-group ions downstream of the bow wave of Comet Giacobini-Zinner for parameters observed during the ICE (International Cometary Explorer) flyby, and (4) water-group pickup ions downstream of the bow wave of Comet Halley for parameters observed during the Giotto flyby. These calculations represent the first treatment of stochastic acceleration in which the back-reaction of the accelerated ions on the turbulence is included self-consistently. The helium calculation reveals some modification of the solar wind wave spectrum and energy diffusion of the ions, while the hydrogen calculation shows extreme damping of the solar wind wave spectrum in the cyclotron-resonant frequency range coupled with a drastic reduction of the acceleration rate of most of the ions. They suggest that this behavior is responsible for an underabundance of hydrogen relative to the minor ions in the anomalous cosmic ray component, which is thought to originate from pickup ions accelerated at the solar wind termination shock.

Solar Interior and Lower Atmosphere Section

Although the variability of the sun is small relative to its total energy output, or relative to the variability of some other stars, fluctuations in the solar output of radiation, fields, and energetic particles are responsible for significant changes in the space environment surrounding the earth. Such changes are known to cause significant perturbations of the upper atmosphere of the earth, and they might also be a natural cause of climatic change.

Solar magnetic activity is the driver for the known variability of the sun on time scales ranging from seconds to decades (and perhaps longer). The source of solar activity lies in the interior of the sun, and it is believed to result from the interaction of convection and rotation in the outer one-third of the solar envelope: the solar dynamo. It manifests itself at the surface of the sun and above in a variety of fascinating phenomena including sunspots, solar flares, prominences, and coronal mass ejections. These phenomena are interesting subjects of study in their own right as they represent the physical behavior of magnetized plasmas in regimes unattainable in terrestrial laboratories, and as they are perhaps the only physical system where we may reasonably hope to understand in detail those processes responsible for a wide variety of astrophysical phenomena. Their study is indeed important to improved understanding of the physical system that drives the variability of the local space environment of the earth.

The long-range goals of the Solar Interior and Lower Atmosphere Section are then (1) to explore the physical state of the interior of the sun by whatever means are appropriate, including the surface diagnostics (such as observed magnetic field structure and solar oscillations) and theoretical modeling; (2) to improve our understanding of the physical state of the lower part of the observable solar atmosphere (the photosphere, chromosphere, and chromosphere-corona transition region) using observational, theoretical, and numerical techniques; and (3) to develop the detailed physical connection of processes observed in the atmosphere to those inferred for the interior, the corona, and the interplanetary medium. Emphasis is given to investigation of phenomena related to the magnetic activity cycle, including their relationship to and consequences for the upper solar atmosphere. These goals are broadly interpreted to encompass the study of the "quiet" solar atmosphere which also participates in the solar activity cycle and whose phenomena (such as granular convection and intense magnetic "flux tubes") are important components of the larger problem of solar magnetic activity. In the following paragraphs a brief description is given of aspects important to the study of the solar interior and lower solar atmosphere in order to set the stage for the following, more detailed descriptions of research in this section during fiscal year (FY) 90.

Radiation is believed to transport most of the energy outward from the center of the sun to a distance of about two-thirds of the solar radius. At that point, the opacity of the plasma increases dramatically due to the lower temperature, and convection becomes the dominant means of energy transport. Standard models of the interior of the sun are unable to match precisely the observed frequencies of the solar p-mode oscillations, and these models emphasize the reality of the solar neutrino problem. A knowledge of the physical state of the solar interior is needed not only to understand stellar evolution, but also to explore the origin of solar and stellar magnetic activity. One long-range goal of the section is to improve our observable diagnostics of the solar interior in order to constrain our knowledge of the variation in temperature, pressure, density, and rotation with solar radius and latitude. Such information is of utmost importance to improving the theory of the solar magnetic dynamo operating in the solar convective region, and to improving our knowledge of the physics of convection as well. The approach to these problems is both theoretical—investigation of the dynamo process and the mechanisms for generation and propagation of solar oscillations—and observational—through the acquisition and analysis of oscillation data.

Study of the sun provides us with details of magnetic activity in one star at one particular moment of its evolutionary history. Through observation of other stars at different evolutionary states, with rotation rate, mass, and chemical composition differing from that of the sun, we may be able to further constrain the physical processes causing magnetic activity. Two approaches to the observational study of activity in other stars are currently being pursued at HAO. First, indicators of stellar magnetic cycles and rotation are accessible in spectra of stars taken over a period of time. The second technique is very new: the attempt to observe nonradial p-mode oscillations of other stars. If stellar oscillations are observable (as suggested by recent observations reported below), then these data will provide precise information on the conditions within other stars in a similar way that solar oscillations probe the interior of the sun. HAO plays a leading role in this new and potentially powerful area of astrophysics: asteroseismology.

The visible surface of the sun is known as the photosphere. It represents the interface at which the transport of energy suddenly changes from dominantly convective in the interior to dominantly radiative in the lower solar atmosphere, and above. The photosphere is thus a region of "convective overshoot." The study of its structure, or granulation, is the foundation for understanding the convective and radiative processes that govern the physical makeup of stellar atmospheres. The "quiet" solar photosphere can be characterized as a dynamically restless radiating plasma that is threaded occasionally by very small, isolated, and quite intense concentrations of magnetic flux ("flux tubes"). Within the isolated flux tubes, the convective transport of energy is partly suppressed. The gas pressure within the tube is significantly reduced relative to its surroundings, the lowering of pressure being compensated for by the magnetic pressure. This effect, along with the small lateral dimension of flux tubes, allows them to be nearly transparent to radiation from the surrounding hot convective region. Thus the radiation from the "walls" of flux tubes overrides the convective deficit and produces an apparent brightening of the feature. The variability of the total solar irradiance associated with the solar magnetic cycle has been linked recently to the number of these small-scale magnetic flux tubes in the solar photosphere.

Variability of the total solar irradiance on shorter time scales has been observed to be associated with the life cycle of individual solar "active regions," which are identified by the presence of large-scale magnetic concentrations such as sunspots and pores. Unlike flux tubes, these features are large enough that the radiative exchange of energy with the surrounding vigorous convection is insignificant in comparison to the reduction in convective energy transport, so that the features appear dark. Associated with these photospheric features are locally induced subsonic flows that, in the case of sunspots, are known as the Evershed flow. The nature of the stability and thermodynamics of these magnetic concentrations is one of the major puzzles for solar physics, and quantitative understanding of their structure is a major goal of the section.

In the chromosphere, which overlies the photosphere and is transparent to the bulk of the photospheric radiation, the nature of the energy supply changes. It appears that the dissipation of mechanical energy from waves and/or the dissipation of electric currents induced via horizontal motions of field footpoints provide the main energy source. Whether this energy is released in situ or propagates to this region from below (via waves) or from the corona above (via either energetic particles or conduction), or both, is poorly understood. Furthermore, there is increasing evidence that the mechanism responsible for heating the chromosphere is distinct from that for the corona. Also evident is that associated transient motions frequently have nearly sonic velocities, yet they are contained, being "frozen in" by the local, nearly force-free magnetic field.

Such complex interactions between a flowing, radiatively cooling plasma and the local magnetic field are evident over the entire solar surface, but are especially pronounced in active regions. For the most part, these are regions of closed magnetic fields in which the corona, transition region, and chromosphere are intimately tied. The enhanced magnetic flux in the active regions is accompanied by enhanced radiative output as well as flaring: the dramatic conversion of magnetic energy into radiative energy, both thermal and nonthermal, and kinetic energy associated with violent bulk motion at chromospheric levels and above. Similar phenomena appear to occur on a reduced scale outside active regions.

Even though the solar chromosphere and corona contribute only a tiny fraction of the total solar radiative output, these layers give rise to most of the ultraviolet radiation from the sun, which has a strong influence on the upper terrestrial atmosphere. Furthermore, this ultraviolet radiation is many times more variable than that of the integrated solar radiation, and the root of this variability is the solar magnetic field. Therefore, another major long-term goal of the section is to understand the nature and modulation of energy transport and transformation in the solar atmosphere, including heating of the chromosphere, transition region, and corona and heat transport by thermal conduction and advection.

In order to address these problems, scientists in the Solar Interior and Lower Atmosphere Section adopt two fundamental approaches: the inference of the physical state of the solar interior and atmosphere through interpretation of observations, and the development of models (both analytic and numerical) of the solar interior and atmosphere. From the observational side, a vigorous area for investigation of the solar interior involves helioseismology, and the section plays a major international role in this research. The Fourier tachometer, developed jointly by HAO and the National Solar Observatory (NSO), has been operated for a number of years to investigate solar oscillations. The fundamental principle of operation of this device has been adopted for two new oscillations facilities: the Global Oscillations Network for ground-based observations and the Michaelson Doppler imager for observations from space. Scientists in this section will play major roles in both facilities. In addition to the Fourier tachometer, a new instrument is being developed at HAO to precisely observe the oscillatory modes of the sun that are most sensitive to the rotation deep within the core. This instrument, based upon the magneto-optical filter, will also be used to measure winds in the sodium layer in the upper atmosphere of the earth.

A parallel development is occurring in the observational study of the lower solar atmosphere: recent work demonstrates that the physical processes controlling this region take place on very small size scales. Recognizing this, the observational research in this section increasingly centers upon high-resolution solar physics, with particular emphasis upon precision polarimetry to reveal the structure of the magnetic field in sufficient detail for quantitative analysis. To this end, HAO and NSO have led in the development of the advanced Stokes polarimeter (ASP), a new instrument which will provide vector magnetic field measurements with unprecedented clarity and precision. A significant milestone for this project was achieved in FY 90: the first observations of solar magnetic fields were obtained with a prototype instrument. Members of the section also avail themselves of opportunities to conduct observations from both space- and ground-based facilities. Data already on hand from HAO's previous Stokes programs and from the Orbiting Solar Observatory (OSO-8) and SMM satellites, as well as data acquired during observing runs at national or international facilities, form an important component of the research effort. Members of the section are also leading efforts to promote the

Orbiting Solar Laboratory (OSL), a major facility for high-resolution observations proposed for launch by NASA in 1997, and the large earth-based solar telescope (LEST), a complementary high-resolution multinational facility to serve the needs of solar physics in the coming two to three decades.

Theoretical study of the solar interior at HAO now emphasizes the study of mechanisms of generation and propagation of oscillations in the solar envelope, the interaction of oscillations and waves with subsurface magnetic fields, the rotational evolution of solar-type stars, and the solar dynamo. Theoretical study of the lower solar atmosphere is also progressing at HAO in several areas: the improvement of techniques for computation of radiative transfer in spectral lines formed in stellar atmospheres, the transfer of polarized line radiation, the fundamental physics of nonequilibrium plasmas, and radiative and MHD models of such quasi-steady magnetic features as sunspots, plages, and network flux tube structures. These models, when developed, will include the complete energy and momentum balance and appropriate connection with the upper solar atmosphere. Their development presents a difficult challenge that will require several years of effort and a step-by-step approach involving both theoretical modeling and observational programs that provide the data with which models may be tested. The effort will encompass other scientific sections of HAO as well as outside collaborators.

The Solar Interior

During FY 90, the HAO/NSO Fourier tachometer continued to operate in Tucson, Arizona, under Timothy Brown's supervision. Two major sets of full-disk data were acquired during this interval: one in the fall of 1989, the other in the spring of 1990. Both of these sets are of roughly three months' duration, and are expected to show solar p-modes to angular degrees as large as 120. These data will be processed with the principal aim of giving a time-resolved picture of variations in the sun's internal rotation and asphericity with the solar cycle.

In addition to the full-disk data, Brown has also used the Fourier tachometer to acquire shorter sets of high-magnification data, taken with four times the spatial resolution of the full-disk data sets. These observations were mostly intended to elucidate the connection between p-modes and solar active regions, in particular the way in which absorption and scattering of p-modes may be used to infer the subsurface structure of magnetically active regions. One such set of observations was a joint observing program involving simultaneous observations with the Fourier tachometer and with the vacuum tower telescope at NSO/Sunspot, performed in collaboration with Frank Hill and Deborah Haber (both at NSO). These observations are in the process of reduction, as are similar ones obtained the previous year in a joint project with John Thomas (NCAR affiliate scientist, University of Rochester), Bruce Lites, and Thomas Bogdan (discussed below under "Sunspots and Flux Tubes").

The comprehensive analysis of old Fourier tachometer data sets, begun last year, proceeded well during FY 90. Several of the shorter full-disk data sets (up to about 55 days in length) were reduced to the point of producing time series and power spectra of the Doppler signal in various spherical harmonics. However, recent evidence from other institutions has made it clear that the methods of time series analysis hitherto employed are prone to systematic errors. These errors are small enough that, five years ago, they could be ignored. But smaller random errors (from longer and better data sets) and improved methods of interpreting the data have conspired to increase the importance of these previously negligible errors. As a result, Brown and Jesper Schou (HAO graduate research assistant) in FY 90 began an effort to understand and, as far as possible, reduce the systematic errors connected with oscillations time series analysis. Clearly, one cannot properly assess the systematic errors in an analysis procedure unless the correct answers are known. Thus, the first step toward achieving the desired understanding has been to write a program to produce extremely realistic time series of artificial oscillations data, using specified mode parameters as input. At the end of FY 90, this program had been completed and most of its functions tested. The next stage of the program will be to use it to test the performance of most of the existing methods of oscillations time series analysis, and in addition to implement and test at least two methods (borrowed from geophysics) that have not yet been tried.

Kumar, in collaboration with Peter Goldreich, Bruce Murray, and James Willett (all of California Institute of Technology), investigated the origin of frequency increase of the solar acoustic modes between 1986 and 1989, reported by Kenneth Libbrecht and Martin Woodard (both of California Institute of Technology). The magnitude of the observed frequency shift is about 0.3 μHz at 3 mHz, which increases rapidly with mode frequency in the range 1–4 mHz, and then drops suddenly. These features together with the small change in the solar luminosity during the same period (less than 0.1%) enabled these collaborators to determine the location and nature of changes in the solar structure over this period. The change in the solar structure responsible for the observed frequency shift is found to be confined to the outer part of the convection zone and the atmosphere above it. Decreasing entropy in the atmosphere gives rise to positive change in the mode frequency. However, in order to explain the magnitude of the frequency shift one needs about ten times larger change in the entropy than is consistent with the change in the solar luminosity. Therefore, change in the entropy alone cannot be responsible for the frequency shift. Another quantity that obviously changes with the solar cycle is magnetic field. It is found that a combination of the entropy and the magnetic field variation neatly accounts for the observations.

During FY 90, Brown became interested in propagating sound waves within the solar atmosphere, and in the circumstances in which such waves might be generated. A theoretical investigation of this question led to the conclusion that the sources of such waves may be visible as discrete, energy-emitting locations on the solar surface, with typical sizes of less than 1 Mm and typical separations of about 5 Mm. A preliminary observational study of the matter, using data with high spatial resolution provided by Edward Rhodes (University of Southern California), has failed to reveal these discrete sources. Brown has, however, initiated a further study, using a data set with better spatial resolution obtained in the Canary Islands by Philip Scherrer, David Fernandes, and Peter Milford (all of Stanford University).

Kumar, in collaboration with Lu, investigated the location of the source of acoustic emission which excites high-frequency solar acoustic oscillations (frequency greater than approximately 5.5 mHz). Kumar and Lu showed that in contrast with the trapped solar acoustic oscillations (frequency less than about 5.5 mHz), the position of the peaks in the power spectrum for high-frequency oscillations is dependent on the source location. This was used to determine the location of the source which is approximately 200 km below the visible photosphere. Since the source strength depends on the convective velocity, this investigation opened up a new probe of the upper part of the solar convection zone.

Kumar, in collaboration with Goldreich, derived analytic expressions for the line widths of solar acoustic modes due to radiative and turbulent damping. This work also provided an explanation for why the contribution to the line width at low frequencies (less than 3 mHz) due to these two very different processes is almost equal.

Thompson (now at Queen's College, London), in collaboration with Christensen-Dalsgård and Gough, used existing solar p-mode frequencies to estimate the depth of the solar convection zone. This work was based on the sensitivity of p-mode frequencies to the variation of sound speed with depth in the solar envelope. At the bottom of the sun's convectively mixed zone, the temperature gradient goes abruptly from an adiabatic value to a superadiabatic one. The resulting change of slope in the sound speed vs. depth relation allows a sensitive measurement of the convection zone depth. The convection zone turns out to have a depth of 200 $\pm$ 1 Mm, with the uncertainty in this value arising mostly from uncertainties in the composition of the material in the solar envelope.

Bogdan, along with Fausto Cattaneo (University of Colorado), Andrea Malagoli (University of Chicago), and Robert Rosner (NCAR affiliate scientist, University of Chicago), has begun work on a numerical approach toward understanding the sources of acoustic emission in the convection zone. This detailed numerical study seeks to quantify the acoustic emission from supersonic turbulent convection at high Rayleigh number, and identify the basic sources of sound in chaotic and highly stratified three-dimensional flows that are able to sustain transient shocks. The study relies on numerical simulations currently being carried out on various supercomputers which employ a novel multidimensional implementation of Woodward and Colella's piecewise parabolic method (PPM) algorithm on a 256 x 256 x 56 grid. Throughout the simulation the various fields (e.g., velocity, pressure, temperature, and density) are projected onto the p-mode eigenfunctions at regularly spaced time intervals, and Fourier transforms of these time series will be computed at the end of the simulation. Concurrently, various sources of sound, such as the fluctuating entropy and vorticity fields, are likewise projected out onto the acoustic eigenfunctions in order to ascertain those aspects of the flow that contribute significantly to the excitation and damping of the individual p-modes. By subjecting the numerical PPM simulations of hydrodynamic convection to such close and detailed scrutiny, Bogdan and collaborators hope to elucidate the basic physics of sound production by chaotic turbulent convection and provide insight into the pressing question of the excitation and damping of the solar acoustic oscillations.

As the strength of the dynamo within the solar convection zone depends critically upon the rotation rate of the sun, the evolutionary history of solar and stellar magnetic activity is strongly coupled to the evolutionary history of the rotation. MacGregor and co-workers have previously developed a parameterized description of internal angular momentum transport, together with a direct computation of the rate of angular momentum removal by a magnetically coupled stellar wind, to trace the rotational evolution of solar-type stars. MacGregor and Cohen have extended this previous model to include processes affecting the internal angular momentum distribution during pre-main-sequence evolution. The new model contains explicit treatment of the reapportionment of angular momentum between the radiative and convective regions occurring during contraction to the main sequence. They have calculated the rotational history of a one-solar-mass star from the age of 10^6 years up to the age of the sun, and they find that for a variety of initial conditions, less than 20% of the initial angular momentum is lost during pre-main-sequence evolution. Because most of this loss occurs just prior to the time of arrival on the zero-age main sequence, the surface rotation rate increases with age for the first few tens of millions of years of evolution in this model. They also find that modest ($<$ 50%) differences in the magnitude of the coupling time between the core and the envelope during the pre-main-sequence contraction can lead to significant differences in surface rotational velocity during early main-sequence evolution. Such an effect may contribute to explaining why young (age $< 10^8$ years) clusters contain *both* rapidly (V sin i $>$ 50 km/s) and slowly (V sin i $<$ 10 km/s) rotating G-type stars of the same age.

MacGregor and Paul Charbonneau (visitor, University of Montreal, Quebec, Canada) have begun a study of how the presence of a poloidal magnetic field in the radiative interior of the sun might assist in enforcing uniform rotation within that region. As a first step toward understanding magnetic transport of angular momentum, they have solved a simpler, Cartesian problem which is the MHD analog of Rayleigh's investigation of the motion of a flat plate through a semiinfinite viscous fluid. In this problem they assume an initial static, uniform fluid of constant kinematic viscosity and resistivity above a flat, conducting plate, with a uniform magnetic field normal to the plate. The plate is given a constant velocity parallel to its surface, and the induction and momentum equations for the time evolution of the fluid velocity and shear-generated field are solved in the domain above the plate. The problem is characterized by both magnetic R_m and viscous R_v Reynolds numbers. In the limit that both R_m, $R_v \gg 1$, the shear imposed at the boundary is transmitted throughout the fluid by a propagating Alfvénic disturbance. In the low-Reynolds-number limit (R_m, $R_v \sim 1$), the transverse flow imparted at the boundary is transported diffusively in the y direction. They have investigated the force balance and magnetic geometry in both limits for two cases: a fluid that is initially uniform and a fluid with a specified density stratification. The problem has also been extended to the simplest case of spherical geometry: a purely radial poloidal magnetic field contained within the volume between an outer rigidly rotating spherical shell and an inner rigidly rotating spherical core.

The variation of the solar rotation rate with depth at the present epoch is an important boundary condition, not only for these studies of stellar evolution, but also for understanding the source of stellar magnetic activity. The rotation rate deep within the sun is of particular interest, but it is also particularly difficult to measure using helioseismology techniques, as only the oscillatory modes of lowest degree penetrate deeply into the interior. The $l = 1$ modes, corresponding to spherical harmonics of degree 1, have been observed in integrated sunlight for years, and the frequencies of the modes have been determined precisely as a result. However, the splitting of the prograde and retrograde modes propagating, respectively, with and against the direction of rotation is small enough at $l = 1$ that it is comparable to the width of the modes themselves. One way to break this degeneracy is to observe the oscillations with modest spatial resolution, but the large signal from solar rotation, coupled with guiding errors of such an imaging device, render this technique unsuitable for the low-amplitude $l = 1$ modes. Steven Tomczyk and Alessandro Cacciani (visitor, University of Rome, Italy), are constructing a novel instrument that incorporates the advantages of observing in integrated sunlight, yet is sensitive to the rotational splitting of the $l = 1$ modes. The instrument is designed to measure fluctuations in the width of a solar absorption line at the same time that it measures the net line Doppler shift. In effect, this information produces the rudimentary spatial information needed to measure separately the prograde and retrograde $l = 1$ modes. The instrument is based on the principle of the magneto-optical filter which has been used in the past to produce Doppler images of the sun with high wavelength stability. A prototype instrument now under construction at HAO will produce initial data in 1991. The same instrumentation will be used by Tomczyk and Paul Hays (visitor, University of Michigan) to observe gravity waves from the sodium airglow emission (see the discussion on gravity waves in the report from the Terrestrial Interactions Section, below).

Stellar Oscillations

Brown, in collaboration with Ronald Gilliland (now at the Space Telescope Science Institute), finished during FY 90 the first analysis of time series photometric data of 212 stars in the old galactic cluster M67. The purpose of this study was to understand (and perhaps extend) the limits to ground-based CCD time series photometry, and ideally to detect sunlike pulsations in the F-type subgiants near M67's main sequence turnoff. The first goal was clearly achieved: typical noise levels of 10^{-3} magnitudes root mean square were attained on a routine basis, for 60-sec exposures on stars of magnitude less than about 12. Moreover, the main sources of noise in the data could be easily identified as atmospheric scintillation and photon statistics. The second goal was not reached, though it was possible to set a 4-σ upper limit of 10^{-4} magnitudes on the per-mode pulsation amplitudes of about 20 target stars. This limit corresponds to about 30 times the solar pulsation amplitude. A number of serendipitous discoveries turned up in the examination of these photometric data, including seven new periodic or multiperiodic variables (2 W UMa stars; 4 δ Scuti stars, all of which are also blue stragglers; and one probable AM Her star), and several stars that show night-to-night variations of several millimagnitudes, quite possibly as a result of rotating features (spots) in their photospheres.

In the realm of stellar Doppler spectroscopy, Brown and Scott Horner (HAO graduate research assistant) in collaboration with Rosner, began work on a laboratory echelle spectrograph in FY 90. This instrument is being constructed with the goal of understanding how to make stellar Doppler measurements that are both extremely precise and extremely stable. To this end, it is necessary to investigate the sources of spectrograph instability in a laboratory setting, so that the interaction between stabilization techniques and methods for increasing transmission may be understood. The spectrograph under construction is intended to behave much like an observatory bench-mounted echelle, but rather than observing stars, it will be used to compare two nominally stable laboratory sources to one another. As of the end of FY 90 construction of the spectrograph was proceeding on schedule, and preliminary results were expected about the end of FY 91.

Sunspots and Flux Tubes

Sunspots are probably the most familiar structures of the solar atmosphere. However, many of their fundamental properties, such as the structure of their magnetic fields, are poorly understood, challenging our best efforts in high-resolution observations and the study of magnetized, radiating plasmas. They also represent the best opportunity to observe and understand the physics of convection in a strong magnetic field.

Lites and collaborators Göran Scharmer (Royal Swedish Academy of Sciences, Stockholm), Thomas Bida (HAO graduate research assistant), and Anders Johannesson (University of Lund, Sweden) continued their observational study of convection in the strong field limit. They examine the fine structure of sunspots revealed by spectra of extremely high angular resolution obtained at the Swedish Solar Observatory on the island of La Palma, Canary Islands, Spain, during 1987 and 1988. By observing Zeeman-sensitive lines of neutral and ionized iron, they determined that tiny bright features within sunspot umbrae ("umbral dots") show no significant magnetic field or vertical velocity changes with respect to their surroundings. It is likely that umbral dots are the observational signature of the convective process in strong magnetic fields, and these findings restrict the range of possible mechanisms for such convection. In particular, the lack of observed changes in magnetic field structure suggests that the convective process is overturning convection confined to slender vertical convective structures below the surface. Thus, the "spaghetti" model of sunspots in which the magnetic flux breaks up into a number of slender flux tubes below the surface is reinforced by these observations, but the absence of significant flows associated with these features indicates that the energy transport is radiative, not convective, near the surface. This inference suggests that the convective plumes below the surface of sunspots are indeed slender—about the size of the dots themselves—and their upper cusp must penetrate very close to the surface.

Bida continued similar observational investigation of the observed two-dimensional structure of sunspots using these spectra. He has found that flows are nearly absent from the umbral and inner penumbral areas of the sunspot studied. He also noted a smooth variation of the strength of the magnetic field within the penumbra in spite of the dramatic intensity fluctuation associated with penumbral filaments. The degree of correlation of Doppler motions, largely from outward Evershed flow, with the observed intensity structure is large on the limbward side of the sunspot, but suppressed on the disk center side, an effect that is not yet understood. Also noted are very large downflows associated with the ends of penumbral filaments.

The prototype ASP (described below) provided first observations of the vector magnetic field structure of a small sunspot with high angular resolution. Analysis of these data by Lites, David Elmore, Graham Murphy (Advanced Study Program postdoctoral fellow), Andrew Skumanich, Tomczyk, and Richard Dunn (NSO) has revealed that, like the larger sunspots observed with the Stokes II instrument, the magnetic field in the penumbra was found to be inclined at a significant angle to the horizontal, even at the outer edge of the sunspot. Remarkably, the central field strength of this small sunspot was nearly identical to that of the Stokes II sunspots, as was the radial variation of the vertical component of the field strength. Unlike the larger sunspots, however, the small sunspot exhibits a significant nonpotential field structure as evidenced by the significantly larger horizontal component of field.

Efforts to model the magnetostatic structure of sunspots and flux tubes, including a more realistic treatment of the energy balance and multidimensional radiative transfer, are in progress by MacGregor, Pizzo, and Paul Kunasz (unaffiliated). If the energy equation is to be incorporated properly into such models, they must embrace the effects of transport of energy by convection (below the visible surface), by radiation (in the visible layers, and within thin magnetic structures), and by as yet unspecified processes in the chromosphere and above. They have incorporated radiative energy transport into Pizzo's earlier magnetostatic models in a physically realistic way, and they treat other energy transport mechanisms (convection and nonradiative heating of the upper layers) as a parameterized energy input spatially distributed within the model. The multidimensional treatment of the radiative transport is essential to a physical representation of the boundary layer between the sunspot and the field-free medium outside. This formidable task of merging these numerical techniques has been accomplished in FY 90, and solutions have been obtained for both the force and energy balance in two-dimensional slab geometry using a grey absorptive opacity, local thermodynamic equilibrium (LTE), and a nonradiative heating function that is specified as a function of height in the upper layers. For layers in the model that are unstable to convection, the model is forced to obey an adiabatic stratification. Lower boundary conditions of the model deep in the convection zone may satisfy one of two conditions: (1) ρ = constant (magnetic inhibition of convection), or (2) T = constant (free convective transport). They found that two-dimensional radiative effects become important only for models with boundary condition (1) where convection is inhibited at the lower boundary by the magnetic field, and then only for flux tubes of quite small diameter ($\leq$ 100 km). For models with larger tube diameter, or with boundary condition (2), the structure along a vertical slice through the atmosphere resembles a one-dimensional plane-parallel model.

The observational parameters available for spots on other stars are more primitive: in the mean, total area, temperature, and, in some cases, magnetic field strength. Those performing a theoretical analysis of sunspot structure should bear in mind the issue of how such parameters might scale from star to star. Most, if not all, theoretical studies address the nature of spots under solar conditions because this is the circumstance that is known in most detail. Skumanich reviewed such studies, but from the point of view of how their results might scale to other than solar conditions. Both the subsurface and above-surface magnetic structure were reviewed for a variety of theoretical "conjectures" including both current sheet and distributed current models. He found that lateral MHD force balance with the ambient surrounding atmosphere leads to a fairly simple scaling relation in which the product of the square root of the pressure excess between ambient and interior with the area of the flux tube is essentially constant with depth and equal to the emerged magnetic flux. Thus, at the surface, the *mean* field strength (flux per unit area) scales as the square root of the ambient pressure *not only* for thin magnetic flux tubes *but also* for spots. Extant observational evidence is found to support such a "universal" scaling law. The issue of the magnitude (on the average) of the erupted flux, and hence of spot area, must be addressed by dynamo models rather than by models of spot structure.

Any observational information that bears on the subsurface structure of sunspots and flux tubes is vital to the efforts described above to model such structures. Much of the effort to date has used observable signatures at the surface as an upper boundary condition, and as the only observable constraint. A new realm of investigation is now opening using the scattering of p-mode oscillations by sunspots and flux tubes to infer subsurface conditions. Observational work in this area has been in progress by several groups within the past few years. Bogdan, Brown, Lites, and Thomas have begun an observational program using the Fourier tachometer and the vacuum tower telescope at the NSO/Sacramento Peak to simultaneously obtain observations of p-modes in the vicinity of sunspots with intermediate and short horizontal wavelengths. Work progresses for analysis of these data.

During the past few years Bogdan, with co-workers, has mounted a sustained effort from a theoretical perspective in order to clarify the complex physical nature of the interaction of waves and oscillations in nonuniform magnetic field structures in both the solar interior and atmosphere. He has made considerable progress in the past year in extending his theory to embrace a more physically realistic situation: the modification of the theory to include (1) gravitational stratification of the atmosphere, (2) multiple scattering of acoustic waves by a pair of identical flux tubes, and (3) the inclusion of radiative damping into the scattering problem.

A common problem of most sunspot/p-mode scattering paradigms is the neglect of vertical stratification. That such neglect is a serious compromise follows immediately from noting that density scale height near the solar surface is on the order of 100–200 km while at the same locations the local acoustic cutoff frequency is comparable to the typical p-mode frequencies. The reason for the omission of vertical stratification in theoretical studies of sunspot seismology is that the governing equations become intractable from an analytic and even to some extent a numerical perspective. The single exception is the uniformly magnetized flux tube where the magnetic field is everywhere parallel to gravity, which was first studied by Ferraro and Plumpton, and has subsequently been employed by Thomas and collaborators to study resonant oscillations in sunspot umbrae. Bogdan and Dieter Schmitt (visitor, Göttingen University, Germany) have extended these previous calculations by embedding a flux tube into an adiabatically stratified polytrope and allowing the oscillations within the flux tube to couple directly and naturally to the p-modes of the surrounding unmagnetized atmosphere. One novel feature of this equilibrium which is inherently absent in the unstratified model is the ability for an incident p-mode from one of the "ridges" of the $k - \omega$ power spectrum to be scattered and appear on other ridges at the same temporal frequency. An important result of this work will be to determine branching ratios between the incoming power in one ridge and the outgoing power in the other ridges as a function of the parameters which govern the equilibrium.

Motivated by the outstanding question of whether sunspot seismology can distinguish between the competing monolithic-flux-tube and spaghetti models of the subsurface magnetic field of a sunspot, Bogdan and David Fox (former summer undergraduate student, now at Princeton University) consider the interaction of an acoustic plane-wave with a pair of uniformly magnetized flux tubes embedded in an unstratified atmosphere. They demonstrate that this interaction falls within one of three distinct regimes depending upon the separation of the magnetic flux tubes and their individual scattering strengths. At the largest flux tube separations the scattering is incoherent and the net scattering cross section is just the sum of the scattering cross sections of the individual tubes. At intermediate separations phase coherence between the acoustic waves scattered by the individual flux tubes leads to cross sections that deviate considerably from the incoherent scattering cross section. At the closest flux tube separations a multiple scattering regime can exist, where the acoustic field scattered by an individual flux tube differs significantly from that which would be obtained in the absence of its companion flux tube. Their estimates suggest that the interaction of the acoustic oscillations with a spaghetti sunspot will almost certainly show coherent phasing of the scattered waves, and will most likely show significant multiple scattering effects. Of these novel effects, a new class of scattering resonances deserves special mention. These resonances are situated on the thin fluid channel that separates two magnetic flux tubes in close proximity, and unlike their counterparts on a single isolated magnetic flux tube, the tube modes whose excitation provides the resonance scattering propagate rapidly along the pair of flux tubes at speeds which are only slightly sub-Alfvénic. This implies that it should be relatively easy for the p-modes to couple to this new class of fast tube modes. Their results offer much preliminary encouragement that sunspot seismology will be able to distinguish between the monolithic-flux-tube and spaghetti sunspot models, although any definitive conclusions must await the extension of this work to flux tube bundles containing several individual flux tubes embedded in a gravitationally stratified atmosphere.

The influence of the radiation field in mediating the interaction between the solar acoustic oscillations and an isolated magnetic flux tube was investigated by considering appropriate modification of the sunspot seismology paradigm developed by Toufik Abdelatif (Center for the Development of Advanced Techniques, Algiers) and Thomas. Bogdan and Michael Knölker (visitor, Kiepenheuer Institute for Solar Physics, Germany) worked out the interaction of an acoustic plane-wave with a uniformly magnetized flux tube of circular cross section that is in both mechanical and radiative equilibrium with a surrounding homogeneous radiating fluid. The radiation field is treated by using the full frequency-integrated equations of radiation hydrodynamics as given by Dimitri Mihalas (NCAR affiliate scientist, University of Illinois) and Barabara Mihalas (National Center for Supercomputing Applications), assuming local thermodynamic equilibrium and the Eddington approximation. The presence of the radiation field introduces an additional wave mode, the so-called radiation-diffusion mode, that is not present in the Abdelatif and Thomas paradigm; it also serves to modify the propagation characteristics of the familiar acoustic and magnetoacoustic wave modes, primarily through radiative damping of these waves. In the presence of a radiation field, the acoustic plane-wave incident upon the magnetic flux tube excites standing internal magnetoacoustic and radiation-diffusion modes within the flux tube, and it couples to scattered acoustic and radiation-diffusion modes in the external unmagnetized fluid. The mode conversion of the acoustic to radiation-diffusion modes at the flux tube surface takes up some of the acoustic power that would otherwise have resided in the outgoing scattered acoustic wave, giving the appearance of acoustic absorption. Through examples that sample the parameter space relevant to the interaction of the solar acoustic oscillations with surface magnetic flux concentrations, Bogdan and Knölker concluded that such mode conversion is likely to be inconsequential for typical solar conditions. They did note that in isolated circumstances the radiation field could have a profound influence on the flux-tube scattering resonances studied by Bogdan; in particular, they were able to demonstrate that complete (i.e., 100%) mode conversion was possible for such resonant interaction. However, they concluded that this type of acoustic absorption was probably not responsible for the ubiquitous absorption of p-modes by sunspots as reported by Douglas Braun, Barry LaBonte (both of the University of Hawaii), and Thomas Duvall (Kitt Peak National Observatory).

Flares and Active Regions

The analyses of the Stokes II January 1980 data set dealing with successive rasters of an active region that had a moderate (class C) X-ray flare continues. Skumanich and Lites found that a pattern of multiple reversals with wavelength in the Stokes net circular polarization parameter, V, forms due to the incomplete cancellation of this parameter from opposite polarity regions within a resolution element. Such was the case with the observations of magnetic polarity reversal line associated with the January 1980 two-ribbon (along the solar surface) flare. The multiple reversals represent a sensitive signature of the magnitude of the relative motions in the opposite polarity regions as well as the degree to which they fill the resolution element. Preliminary analysis of a raster just before the flare indicates that magnetic elements along the polarity reversal line had a motion such that opposite-end segments of the line were moving towards the nearest opposite polarity spots that "anchor" the ends of the neutral line. The relationship of this flow to the flare and its status after the flare is under continuing study.

The methods for analysis of Stokes polarimetry developed at HAO are being used with increasing frequency by the solar physics community. At the University of Hawaii, Richard Canfield, Yuhong Fan, Kimberly Leka, Alexander McClymont, and Jean-Pierre Wuelser, along with Lites and Hal Zirin (California Institute of Technology), have analyzed vector magnetograms of a flaring active region obtained with the University of Hawaii Haleakala Stokes polarimeter. They find that the flare kernel regions, which are locations of precipitation of nonthermal electrons as evidenced by self-reversed Hα profiles with enhanced blue wing intensities, are coincident with the edges, not the centers, of the vertical current systems as determined from the vector magnetograms. They also developed a novel test for departures of the magnetic field system from a force-free state, and they find that the flaring active region departs from a force-free relationship by amounts significantly exceeding both the statistical fluctuations and the total flux imbalance of the part of the active region covered by the field of view.

The Quiet Sun

Although there has been significant progress in understanding the structure of the quiet photosphere, the quiet chromosphere and transition region remain very much unknown. One of the major issues regarding the transition region involves the relative emission from ions of differing ionization energy, i.e., the emission as a function of temperature in the transition region. Many attempts have been made to explain the emission using classical thermal conduction plus other parameterized energy input mechanisms. Most of these attempts, based on static, plane-parallel models of the atmosphere, have failed to reproduce the observed emission of the sun at temperatures between 10^4 and 10^5 K.

Shoub continues the approach that the problem lies not with specifics of the atmosphere and heating mechanism, but with the microphysics of the plasma. He argues that one must allow for the possibility that the distribution of electron velocities is not described by a local Maxwellian, but is influenced by the diffusion of energetic electrons along the steep temperature gradient of the transition region. These nonthermal electrons affect both the spatial dependence of radiative losses (fast electrons and protons overionize the plasma relative to equilibrium) and the ability of the gas to conduct heat downward from the corona. Moreover, the interpretation of observed EUV lines is affected because of the local perturbation of the ionization balance (i.e., lines are not formed over the same temperature range as in equilibrium). In the process of examining these effects, Shoub has found it necessary to reexamine techniques used in the theory of plasma physics to treat the effects of Couloumb collisions on the evolution of nonthermal electron and proton velocity distribution functions. In the past, an accepted way to model these effects was via a Fokker-Planck collision term which rests on the assumption that the close encounters of particles occur so infrequently that they may be neglected. This Fokker-Planck collision term may be derived from the more fundamental Boltzmann integral, which treats the effects of both close and distant encounters. He has compared numerical solutions of the full Boltzmann equation to those of the Fokker-Planck equation for the simple case of the relaxation of an isotropic test particle distribution colliding with a fixed Maxwellian background of equal-mass particles. In the course of this work, Shoub developed an effective numerical approach for solving the Boltzmann equation for other than hard-sphere interactions. The results of his work show that when the initial test particle distribution is not too different from that of the background (to which it eventually thermalizes) then close encounters play a minor role. If, however, the initial test particle distribution is quite different from the background distribution—conditions that may be encountered, for example, in solar flares where highly energetic electron beams impinge upon the chromosphere and are slowed by electron-electron collisions— close encounters *dominate* the evolution of the distribution function. In particular, including the effects of close encounters may reduce the thermalization times by *an order of magnitude or more* over those calculated using the Fokker-Planck collision operator. The reason for this may be traced to the ability of the close encounters to scatter energetic particles to much lower energies where the Couloumb collision frequency is much larger, hence leading to rapid thermalization of the energetic particles. This work has implications for the discipline of plasma physics at a fundamental level, implications that go well beyond the applications in solar physics or even astrophysics.

Grant Athay (now a visitor) and Kenneth Dere (U.S. Naval Research Laboratory) have continued their interpretation of the EUV emission line data from the high resolution telescope and spectrograph flown on Spacelab II with the intent of understanding the structure and diagnostics of the chromosphere-corona transition region. They adopt a statistical approach to the study of a large number of individual structures observed on the solar disk. Their results suggest that many of the often-used "density-sensitive" EUV line ratio diagnostics of the chromosphere and transition region are seriously compromised by optical depth effects along the line of sight. Thus, for these lines not only the density but also the temperature and, in particular, the volume of the emitting material in a laterally inhomogeneous atmosphere play significant roles in the intensity changes of these lines from point to point on the solar disk. A parallel study of the observed statistical distribution of Doppler shifts in chromospheric and transition region lines suggests that the plasma flow is divergent from the tops of closed magnetic "loops," and that the plasma more or less fills the magnetic loops from which most of the radiation originates. These data suggest that the temperature gradient across the magnetic field lines is large and that alternation from cool to hot loops occurs on spatial scales much less than the resolution limit of the observations (roughly one arcsecond).

Stokes Polarimetry

A major new instrument for observing the detailed structure of the vector magnetic field within the solar atmosphere is nearing completion. The ASP is a collaborative effort between HAO and the NSO. It will be located at the vacuum tower telescope at NSO/Sunspot. The promise of a dramatic increase in angular resolution for Stokes polarimetery, accompanied by unprecedented precision in the accuracy of the field measurements, was emphasized by results from an observing run with the ASP prototype instrument (see the discussion of sunspot observations above) carried out in May and June 1990. In addition to the new scientific results, the observing run provided the opportunity to verify the end-to-end design of the system, evaluate the performance of the calibration procedure, constrain the specifications of the final optical elements, and produce sample data for the development of analysis software. The instrument and the observing run were highly successful, and problem areas in both the hardware and the calibration procedure were identified and are being corrected. The full instrument is expected to be deployed in mid-1991. Following that, observing campaigns of roughly two to three weeks each will be carried out several times a year for the next three years during an epoch of high solar magnetic activity.

One of the major concerns for successful operation of the ASP is the polarization calibration of the entire system. During 1990 a great deal of effort was devoted at HAO to understanding this problem, both from a theoretical perspective and using the results generated by the ASP prototype instrument. Skumanich and Murphy have considered the information content, singularity (i.e., the issue of well-posedness), and uniqueness of the ASP calibration method using rotations of the calibration optical elements—polarizer and retarder (both singly and in tandem)—as a means of introducing known calibration polarized states to characterize the 16 unknowns representing the polarization of the ASP polarimeter. In the absence of errors in the calibration optical elements and the primary light source, a minimum calibration set of four angular positions (e.g., three polarizer and one polarizer-retarder positions) is sufficient for a complete and accurate calibration. Unfortunately, such exact elements and sources are not readily available. Consequently, additional angular positions are needed, but this introduces redundancies and underdetermination into the method. Thus, an important aim has been to ascertain whether the characteristics of the polarimeter can be defined sufficiently accurately, given realistic constraints of time and energy. For example, though desirable, is it feasible to make a fine rotation set of calibration measurements both before and after each observation? Towards answering this question, Murphy has examined mathematical models of the optical system, ranging from a simplified one with 6 unknown elements to more realistic ones with about 50. From these, it has been possible to identify inherent limitations in in situ calibration methods. Moreover, in complement with the work of Tomczyk, Peter Stoltz (summer undergraduate student, now at the University of

Colorado), and Paul Seagraves (described below), the necessity of supplementary laboratory measurements has been demonstrated.

Tomczyk, Stoltz, and Seagraves investigated the systematic errors introduced into the calibration of a Stokes polarimeter with rotating calibration optics (as described above) which deviate from ideal (i.e., known) properties. To accomplish this, they used a linearized treatment of the Mueller calculus which allows for small and arbitrary imperfections in the Mueller matrices of the calibration linear polarizer and retarder, as well as a small amount of polarization of the calibration light source. They find that half of the matrix elements which describe the response of the polarimeter may contain systematic errors related to these imperfections. These matrix elements are identified, and the remainder of the matrix elements may be determined independently (to first order) of the imperfections of the calibration optics. This investigation identified those properties of the light source and calibration optics that must be known from laboratory measurements in order to carry out the calibration. The results of the theoretical study were also verified by numerical simulations of the ASP calibration procedure.

The method for analysis of Stokes profiles developed at HAO is the most powerful and comprehensive in use, but it requires a large amount of computation time to execute. Methods using simplifying approximations will be necessary for quick-look analysis of data from ASP and useful for analysis of extensive data sets, such as time series of magnetic field maps, where a more qualitative description of the vector magnetic field will suffice. Lites and Thomas Metcalf, Canfield, and Donald Mickey (all of the University of Hawaii) have compared results of one such approximate procedure formulated by John Jefferies (National Optical Astronomy Observatories [NOAO]/NSO), Lites, and Skumanich based upon the weak-field approximation with the results of the more exact HAO inversion procedure. The comparison of methods is based upon analysis of actual Stokes profile data from the University of Hawaii Haleakala Stokes polarimeter. The approximate method gives favorable results, provided one avoids strong field regions (sunspots), is satisfied with fluxes rather than actual field strengths of unresolved magnetic elements within the field of view, and is able to accept moderate errors in the orientation of the vector magnetic field.

Solar/Stellar Activity Analog

Skumanich and Arthur Young (San Diego State University) have continued their analysis of the distribution of Hα emission activity on the rapidly rotating, one-half-day period, dwarf K star V471 Tau. This dwarf, whose photospheric temperature is two-thirds that of the sun, is in synchronous rotation with a white dwarf companion whose UV radiation represents an additional driver for the K star's chromosphere. Analyzing data they obtained at NOAO/Kitt Peak, Skumanich and Young found evidence for a ring or disk of Hα material which appears to be supplied or excited by flaring activity on the K dwarf. Whether this material is magnetically confined or is the signature of mass ejection events is under study.

This year was the second season of operation of the HAO solar-stellar spectrophotometer (S^3) at the Lowell Observatory 42-inch Telescope Facility at Anderson Mesa, Flagstaff, Arizona. During the first 120-day operations period in which 15 nights of observation were scheduled alternately with 15 nights of no operation, 1200 stellar spectra and 102 solar spectra were collected. A new focal plane assembly was manufactured and installed before the beginning of the 1990 observing season. The change in the optical system resulted in a factor of two improvement in the signal-to-noise ratio. Data reduction codes have been completed during the past year. It is now possible to produce corrected, calibrated spectra for the stars in the 1990 rotation program. Line profiles and line index parameters are currently available for the strong chromospheric lines, for the helium D3 region, and for the infrared neutral potassium line. Comparison of rotation periods for two of the stars in the 1990 observing list which are jointly observed by the Mount Wilson Ca II photometer indicates that the spectral line indices vary with periods similar to those inferred from the Ca II photometer.

Derek Buzasi (visitor, Pennsylvania State University) and Fisher have used the S^3 to study spectroscopic variability in 89 Her, which is the prototype of a proposed (by Andrea Dupree and Howard Bond) class of stars characterized by low-amplitude, semiregular variability. These stars are believed to be highly evolved, low-mass, old-disk objects that may recently have undergone envelope ejection en route to the planetary nebula stage. The colleagues monitored 89 Her for two months in the fall of 1989, using the Hα, Ca II infrared triplet, and Ca II H and K lines, and they find that the radial velocity of 89 Her, based on lines that are presumably photospheric in origin, is -16 ± 10 km/s, with the relatively large uncertainty due to apparently stochastic variability of this quantity. The Hα line exhibits P Cygni profile representative of a wind with a terminal velocity of 138 km/s, and the calcium lines are exceptionally deep, which may be due to cool, low-density, circumstellar material. (This hypothesis is supported by the discovery of strong Paschen lines in the spectrum.) No short-term periodicity is detected in any of the line fluxes measured.

Radiative Transfer

Jo Bruls (visitor, Utrecht Astronomy Institute, The Netherlands), Lites, and Murphy have begun a program to understand the formation properties of those Fe I lines that are used as magnetic field diagnostics. The aim of this research is to understand how the thermodynamic properties of the atmosphere influence the magnetic fields inferred from the polarization of these lines, and to determine the reliability with which those parameters that describe the thermodynamic state of the atmosphere may be extracted in the process of inversion of Stokes profiles. Traditionally, the thermodynamic properties are much more difficult to obtain than are the parameters that describe the magnetic field. In this study, detailed non-LTE line transfer computations are carried out for complex model Fe I atoms in model atmospheres representing various solar features, and the results of these computations are used as input to the code for synthesis of Stokes profiles. The initial results demonstrate that Fe I lines of medium excitation such as the multiplet at 630.2 nm are more amenable to inversion than low-excitation lines such as those at 525.0-nm, since the latter lines have a much more extreme temperature sensitivity. The assumption of LTE source functions is justified for these photospheric lines, but the line opacity depends upon the overall ionization equilibrium, which departs from LTE in the photosphere and is therefore model-dependent. These computations show that the 630.2-nm lines are formed at roughly the same height in the atmosphere in models ranging from sunspots through quiet sun and plage, so that these lines are excellent magnetic field diagnostics in the middle photosphere.

Ivan Hubeny (visitor, now at GSFC) and Lites succeeded in modifying the Scharmer-Carlsson multilevel non-LTE transfer code to incorporate the effects of partial redistribution of photons in both frequency and angle. The new code demonstrated convergence on one of the most demanding of numerical problems of this type: the Lα transfer problem in the quiet solar atmosphere. This method will allow computations of line transfer with a new degree of realism (by virtue of the inclusion of the redistribution effects in fully self-consistent multilevel treatment of the transfer), speed of computation (by virtue of the treatment of partial redistribution computation as an equivalent two-level atom problem), and accessibility (by virtue of the wide use that the Scharmer-Carlsson transfer code now seen in the astronomical community). The code will prove to be quite useful in a number of areas of research at HAO, including exploration of the fine structure of the chromosphere, investigation of line formation and energetics of the transition region, and polarization transfer problems involving Zeeman-sensitive lines formed in the chromosphere.

Hubeny, in collaboration with David Hummer (University of Colorado), continued the study of line formation in stellar atmospheres. They investigated the sensitivity of model atmospheres of hot stars to the number of levels that must be included in model atoms of hydrogen and helium. They concluded that eight bound levels of hydrogen, rather than the traditional five, are needed to determine the temperature structure and Balmer line profiles of models with effective temperatures ranging from 20,000 to 43,000 K. Similarly, they find that eight levels of He I and 12 levels of He II are necessary to fix the temperature structure of these models.

MacGregor has collaborated with Robert Stencel (University of Colorado) in the study of the formation and flow of dust grains in late-type stellar atmospheres. They use Mie theory to calculate Plank mean radiation pressure efficiency factors for silicate grains of different sizes, and they investigate how the inclusion of grain sputtering affects the dynamics of dust-driven flows. MacGregor and Bogdan are also studying the radiative relaxation of temperature fluctuations in an infinite, grey atmosphere, and the related problem of the effects of radiation on the propagation of acoustic and MHD waves. In this study they solve the time-dependent equation of transfer assuming LTE, but in contrast with previous studies, they do not adopt the Eddington approximation.

Large Earth-Based Solar Telescope

Members of the HAO staff continue their ongoing efforts to promote U.S. participation in the funding of LEST. This past year has seen the development of a proposal to NSF for the U.S. contribution to the design phase of LEST. The U.S. Scientific and Working Group for LEST, chaired by Jeffrey Linsky (University of Colorado), has named Lites as one of three principal scientists on this proposal. The proposal also requests funds for further development of adaptive optical correction of seeing (a development crucial to the success of LEST), which will be carried out at NSO's Sacramento Peak facility and at the Lockheed Palo Alto Research Laboratories. HAO is continuing its support of these ongoing efforts with the goal that LEST will be accessible to the national solar physics community. In particular, its advanced Stokes polarimeter is viewed as an important step toward an instrument that will ultimately be sited with LEST.

In October 1990, a review of the LEST design was carried out in Risø, Denmark. No serious flaws in the design were acknowledged, so that LEST may now proceed with detailed planning and construction phases. The significant task ahead is to secure funding for the U.S. share of this important international initiative of solar research.

Orbiting Solar Laboratory

The Orbiting Solar Laboratory (OSL) will be the single most important solar space experiment planned for the coming decade. OSL is an unmanned NASA space mission that will place a relatively large-aperture (1.0-m) solar telescope into a slowly precessing polar orbit to enable the spacecraft to see continuous solar illumination for about 260 days per year. OSL is planned to produce images and spectra from 220 to 1000 nm with an angular resolution of about 0.13 arcsec at 500 nm. The spacecraft will also carry co-observing instruments to observe at ultraviolet and X-ray wavelengths with angular resolutions somewhat less than that of the large optical telescope. The OSL mission held the position as the 1992 new-start candidate in the NASA five-year strategic plan, but budgetary considerations prevented any major new program to be started in 1992. Based on a 1993 startup, OSL is scheduled for launch in 1998.

Two HAO scientists participate actively in the OSL program. Fisher is the telescope scientist for the OSL, and Lites is a facility scientist. Both serve as members of the OSL Science Working Group.

Terrestrial Interactions Section

Studies of the response of the earth's environment to the variable nature of the sun encompass a wide range of topics, ranging from solar wind/magnetosphere coupling to the modulation of the middle and upper atmosphere by solar radiation. Understanding the chain of events involved in the coupling of solar and auroral energy to the terrestrial environment is a major goal of the Terrestrial Interactions Section.

Raymond Roble, Arthur Richmond, Holzer, and Robert Dickinson (Climate and Global Dynamics Division) are a team that is participating in the NASA Space Physics Theory Program. The management and scientific use of the NCAR Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Data Base also occur within the section.

Thermospheric and Ionospheric Dynamics

The NCAR thermosphere/ionosphere general circulation model (TIGCM) and the new thermosphere/ionosphere/electrodynamic general circulation model (TIE-GCM) have been developed as a collaborative effort by Roble, Cicely Ridley, Dickinson, and Richmond. The model is evolving continuously with the addition of new physical, chemical, radiational, and electrodynamic processes. Last year a self-consistent aeronomic scheme was incorporated into the TIGCM, and considerable work was expended this year in testing and evaluating the model's ability to simulate thermospheric and ionospheric phenomena. The TIGCM now calculates global distributions of neutral temperature; zonal, meridional, and vertical winds; height of the constant pressure surface; number densities of the following neutral species, $n(O)$, $n(O_2)$, $n(N_2)$, $n(N[^4S])$, $n(N[^2D])$, $n(NO)$, $n(He)$, and $n(Ar)$, and the following ion species, $n(O^+)$, $n(O_2^+)$, $n(N_2^+)$, $n(NO^+)$, and $n(N^+)$; and also the electron density and electron and ion temperatures. In addition to the above, the new TIE-GCM calculates the global distribution of electric potential and ion drift.

The TIGCM and TIE-GCM have both been used to calculate the global thermosphere and ionosphere structure for steady-state diurnally reproducible equinox and solstice conditions and for each month of the year for both solar cycle minimum and maximum conditions. These TIGCM runs are being made available to the CEDAR and university communities in general to compare model predictions with average observational data for a monthly period. These monthly predictions are also being compared with empirical model predictions, such as the mass spectrometer/incoherent scatter model MSIS-86 and the International Reference Model, IRI, to determine how well the TIGCM represents the mean structure as defined by these empirical models. The TIGCM predictions are also being compared with available data in the CEDAR database, primarily incoherent scatter radar data, Fabry-Perot interferometer data, and airglow emission data. In general, the agreement between TIGCM predictions and various observations and empirical models is good; however, there are a number of areas where the TIGCM performance needs to be improved. These include the need for a better prescription of the physical processes associated with magnetosphere/ionosphere energy and plasma exchange at the TIGCM upper boundary, the need for a better description of mesosphere/thermosphere exchange processes at the lower boundary of the model, and the need for a better prescription of the variable aurora particle precipitation and ionospheric convection inputs at high latitudes.

The TIGCM has also been used for time-dependent runs, such as modeling specific time periods where data are available for comparison with model predictions. These include the CEDAR equinox transition study (ETS), 20–25 September 1984; the Coordinated Data Analysis Workshop–6 (CDAW–6) interval 20 March–10 April 1979; the 10–15 July 1982 geomagnetic storm and solar proton event; the 20–30 January 1983 geomagnetic quiet period; and the CEDAR lower thermosphere coupling study (LTCS), 20–25 September 1986. These studies use realistic time-dependent auroral inputs based on satellite particle precipitation measurements and satellite measurements of the properties of the solar wind. The results of these time-dependent model runs have been made available to a large number of university scientists for comparisons with data obtained during the period and also for studying the time-dependent responses of the coupled thermosphere and ionosphere system. TIGCM predictions for the two CEDAR study periods have been used in ten papers published in the *Journal of Geophysical Research* during the past year. These time-dependent TIGCM runs reveal considerable variability in the coupled thermosphere and ionosphere system. In order to understand the physical and chemical processes that are operating in the thermosphere in the time-dependent simulations, a considerable number of specialized postprocessors have been developed. These processors allow an analysis of the physical and chemical processes that are operating over a given ground station, along a satellite track, along a radar chain longitude, and at either constant height or constant pressure surfaces. In addition, video techniques have also been developed and used to help in visualizing and understanding the variability in the coupled thermosphere and ionosphere system.

The TIGCM has been developed as a community model, and it has been used for a large number of investigations by graduate students, postdoctoral fellows, visiting scientists, and university collaborators. Some of the studies conducted with the TIGCM during the past year include the following:

Cassandra Fesen (visitor, Dartmouth College) and Jeffrey Forbes (visitor, Boston University) have been using the TIGCM to study the effects of upward propagating diurnal and semidiurnal tides on the properties of the coupled thermosphere/ionosphere system. They have also used the TIGCM to study tidal effects during the CEDAR LTCS campaigns and have compared time-dependent TIGCM predictions with global observations during this geomagnetically disturbed period. Another study by Fesen, Richmond, and Roble demonstrated that auroral disturbances can have a significant influence on the overall structure of the tidal components in the thermosphere.

Gonzalo Hernandez (University of Washington), Roger Smith (University of Alaska), and Roble have used the TIGCM to examine the thermospheric circulation over the South Pole. TIGCM predictions were compared with Fabry-Perot wind measurements made at the South Pole during the past year. The results of this study indicate that the measured winds display a considerable variability but that the mean or average wind pattern is consistent with TIGCM predictions. The main differences between TIGCM predictions and observations appear to be associated with the differences in the overall configuration of the real magnetic field in the Southern Hemisphere polar cap compared with an offset dipole field in the model.

Frank Marcos (Air Force Geophysics Laboratory, or AFGL), Timothy Killeen (NCAR affiliate scientist, University of Michigan), and Roble have continued their investigation into the possible use of the TIGCM for prediction of density variations and satellite drag for operational purposes. During the past year two realistic simulations have been performed and compared with satellite data to evaluate the predictive capability of the TIGCM. The results of these studies have shown that at the present time the TIGCM has a predictive capability that is equivalent to that of the MSIS empirical model. However, if improvements in the specification of auroral inputs can be made based on real-time data, the TIGCM will have a much greater predictive capability than the empirical model. The TIGCM has also been used for a series of studies to quantify the sensitivity of thermospheric density to variations in solar EUV and UV spectral irradiance, auroral particle precipitation and ion convection inputs, amplitudes and phases of the upward propagating tidal modes, and uncertainties of aeronomic chemical reactions, branching ratios, quenching rates, etc. These sensitivity studies are being used to help define a satellite with an instrument complement capable of providing the TIGCM with the inputs needed for the accurate prediction of thermospheric density.

Allen Burns (University of Michigan), Killeen, and Roble have continued to use the TIGCM to study composition changes during geomagnetic storms. They have designed and used a diagnostic processor that analyzes the various forcing terms in the composition equation in the TIGCM to determine the causes of composition changes at various times during and following geomagnetic storms. Their results show that the major changes of composition are associated with vertical and horizontal transport that is balanced by molecular diffusion. They have shown that changes in neutral gas composition can cause enhanced rates of ion chemical recombination and account for the negative phase of a geomagnetic storm.

Geoffrey Crowley (Lowell University) and Roble have also used the TIGCM to study compositional changes during the CEDAR ETS and its effects on ionospheric structure. They showed that TIGCM predictions of composition changes were consistent with observed electron density perturbations observed globally using ionosonde data. This suggests that composition changes have an important role in causing ionospheric perturbations during geomagnetic storms. They also showed that a multiple-cell region of composition density perturbations develops around the magnetic polar regions in response to geomagnetic storms. The TIGCM-predicted structure has been verified with satellite data, and the physical causes of these perturbations are under investigation using TIGCM diagnostic processors.

Stanley Solomon (visitor, now at the University of Colorado) and Roble are continuing their development of a global airglow model to be used with TIGCM output. They have been modeling airglow variations during the great geomagnetic storm of 8–10 February 1986. The results of these predictions compare well with airglow data obtained by James Hecht (Aerospace Corporation) during the storm at the Sondrestrom Fjord radar site. The results indicate that a very large decrease of atomic oxygen occurred in the lower thermosphere during the storm and that TIGCM predictions of the storm compositional perturbation are consistent with the airglow measurements.

Robert Raskin, Jeffrey Thayer, Richard Cannata (all of the University of Michigan), Mihail Codrescu (then HAO graduate research assistant), and Jacqueline Schoendorf (Lowell University) are all graduate students using the TIGCM for their thesis research. Raskin is using the model to develop a vector spherical harmonic model of TIGCM predictions, Thayer is using the TIGCM to examine high-latitude vorticity and divergence fields and compare results with NASA *Dynamics Explorer* satellite data, Cannata is investigating the role of Joule heating in the acceleration of the polar wind, and Schoendorf is using the TIGCM to investigate the cause of the multicellular density structure around the magnetic poles during geomagnetic storms.

Manfred Rees (University of Alaska) and Roble are using the TIGCM to study the atmospheric response to the great red auroral storm that occurred on 13 April 1981. This storm produced exospheric temperatures approaching 2500

K at midlatitudes and caused considerable density perturbations to the coupled thermosphere/ionosphere system.

Maura Hagan (visitor, Massachusetts Institute of Technology) and Roger Burnside (Arecibo Observatory) have been using the TIGCM and incoherent scatter radar data from the CEDAR Data Base to examine the topside structure of the ionosphere over various radar sites. The results of these studies show that there is considerable plasma and energy exchange in the topside ionosphere, and that the parameterization of these exchange processes in the TIGCM needs to be enhanced to account for the observed ionospheric structure.

Richmond collaborated with Douglas Brinkman (University of California, Los Angeles) on the analysis of aurorally generated gravity wave effects in the thermosphere, and the interaction of these waves with the mean meridional circulation. Brinkman completed his Ph.D. thesis on this topic.

Fesen, Richmond, and Roble used the TIGCM to investigate the effects of Joule heating in the auroral zone on the generation of global semidiurnal thermospheric tidal winds and temperature perturbations. Aurorally generated tides during active periods can be comparable to tides propagating up from the middle atmosphere and those generated by thermospheric absorption of solar ultraviolet radiation, and the variable combination of the three can give rise to complex tidal behavior.

Ionospheric Wind Dynamo

Richmond, Roble, and Ridley have developed a dynamo simulation model to operate interactively with the TIGCM, in order to be able to study the mutual physical interactions between thermospheric winds and ionospheric electric fields. Initial simulation runs of the TIE-GCM indicate that reasonable daytime electric fields are reproduced by the coupled model. In a related study, Richmond collaborated with Rod Heelis and David Crain (both of the University of Texas at Dallas) on modeling of interactions between ionospheric electric fields, ionospheric plasma drifts, and electric conductivities in the equatorial ionosphere.

A statistical study of electric fields above the Arecibo incoherent scatter radar, begun in previous years by summer undergraduate students Joyce Berkey (HAO) and Sixto González (NCAR minority summer undergraduate program) and scientist Craig Teply (Arecibo Observatory), was completed by Richmond and Roy Barnes. Stronger electrodynamic drifts occur during solar cycle maximum conditions than during solar minimum, particularly in the east-west direction at night.

Global Mean Structure of the Mesosphere and Thermosphere

A self-consistent global average model of the coupled mesosphere, thermosphere, and ionosphere has continued to be developed and tested for a variety of geophysical conditions. The model is being used to test the overall aeronomic scheme that is being developed for inclusion in a mesospheric extension of the TIE-GCM. Development of this new thermosphere/ionosphere/mesosphere/electrodynamic general circulation model (TIME-GCM) will extend between 30 and 500 km and will be used primarily to investigate physical and chemical couplings between the thermosphere and mesosphere and to determine how deep into the earth's atmosphere the effects of solar and auroral variability penetrate. This new GCM will be used in the analysis of Upper Atmosphere Research Satellite (UARS) data, Solar Mesosphere Explorer (SME) data, and eventually Earth Observing System (EOS) data.

During the past year a diurnal version of the model has been developed and the aeronomic scheme has been tested for a wide variety of conditions. The results indicate that the scheme should work well when it is incorporated into the new TIME-GCM.

The global mean model has also been used to investigate the effects that increasing levels of carbon dioxide and methane will have on the earth's upper atmosphere. These calculations show that the upper mesosphere will cool about 10 K and the thermosphere will cool 50 K during the 21st century as the concentrations of these trace gases double. The model calculations also predict that the upper atmosphere response to solar and auroral variability will be somewhat different from present-day conditions. Increased CO_2 cooling is predicted to damp the upper atmosphere response to geomagnetic activity from present-day conditions.

Assimilative Mapping of Ionospheric Electrodynamics

The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) project has continued to develop and utilize the objective procedure for synoptic mapping of high-latitude ionospheric electric fields and currents using a combination of ground-based and satellite-based measurements of electric fields, ionospheric conductivities, and magnetic perturbations. The period of 23–26 September 1986 (one of the SUNDIAL [global scale ionospheric simultaneous measurements and modeling of responses to solar terrestrial coupling processes] campaign periods) was analyzed by Barbara Emery, Richmond, Lisa Shier (past summer undergraduate student from Rice University); Herbert Kroehl, Chris Wells, John McKee (all of NOAA National Geophysical Data Center); J.M. Ruohoniemi (Johns Hopkins Applied

Physics Laboratory); Mark Lester (University of Leicester); Delores Knipp (U.S. Air Force Academy); Fred Rich (AFGL); John Foster (Massachusetts Institute of Technology); Odile de la Beaujardière (SRI International); Catherine Senior (Center for the Study of Environmental Physics, St. Maur, France); and Sawaka Maeda (Osaka College, Japan). The output of this analysis provided a global view of high-latitude electrodynamics needed by researchers involved in this campaign effort.

Analysis of another day, 23 July 1983, yielded a unique view of the response of ionospheric convection to the changing direction of the interplanetary magnetic field (IMF). This study was carried out by Knipp, Richmond, Nancy Crooker (AFGL), de la Beaujardière, Emery, David Evans (NOAA Space Environment Laboratory), and Kroehl. A strongly northward IMF was found to produce a four-cell ionospheric convection pattern with an afternoon-to-late-morning potential drop of 75 kV, much stronger than commonly thought to exist for northward IMF. Following a southward-to-northward turning of the IMF, the nightside portion of the convection, with an early-morning-to-evening potential drop, slowly decayed with a time scale on the order of an hour, suggesting either a propagation-time effect in the magnetosphere or a flywheel effect associated with thermospheric winds.

Gravity Wave/Airglow Interactions

Hays and Roble have developed analytic and numerical models that investigate the interaction of a gravity and a mesospheric/lower thermospheric airglow emission layer. The two-dimensional models predict composition changes of major and minor upper atmospheric constituents in response to gravity wave passage. The gravity wave model also includes a turbulence parameterization that acts when the gravity wave breaks. The results of these simulations show that the upper mesosphere/lower thermosphere is a dynamically active region of the atmosphere where gravity waves have a significant influence of the chemical background and airglow emission rates. The results of the model are also being used by graduate student Mingzhao Luo (University of Michigan) to help in the interpretation of airglow measurements that she made using a ground-based image plane detector spectrophotometer. This model is being used to help design ground-based and satellite instrumentation for the study of upper atmosphere airglow features.

Hays and Tomczyk are designing an instrument to measure vertical velocities in the sodium airglow emission layer, and the two-dimensional model is being modified to include neutral and ionized sodium to study the characteristics of the expected airglow signatures.

Auroral Physics

Dirk Lummerzheim (visitor, University of Alaska) and Jean Lilensten (visitor, Center for the Study of Random Geophysical Phenomena, Grenoble, France) have designed a new auroral transport code that combines the best features of several existing, but deficient, transport codes to study the interaction of auroral particles with the earth's upper atmosphere. This new model should be numerically efficient, and it will be useful not only for the study of auroral particle precipitation but also as a replacement to the existing auroral parameterization scheme in the TIGCM. This new auroral model should improve the calculation of ionization rates from precipitating electrons in the TIGCM and lead to a better description of the electron density structure in the polar regions.

Lummerzheim, Rees, and Roble are working on developing a fast auroral deposition code that will be used by David Winningham (Southwest Research Institute) in the analysis of data from the particle environment monitor on the UARS spacecraft. Using UARS data and the transport code, information will be obtained on auroral ionization rates, heating rates, and dissociation rates of ionospheric and atmospheric constituents that will be used in the TIGCM for modeling specific periods during the UARS mission.

Lummerzheim, Rees, and Roble are also developing inversion techniques for recovering auroral particle characteristics, such as characteristic particle energy and energy flux, from *Dynamics Explorer* auroral airglow image data. Ratios of airglow emission rates from images having different wavelength filters allow these parameters to be determined. The global image data are being used to calculate ionospheric conductances that in turn will be used along with the AMIE technique for deriving other ionospheric electrodynamic parameters. These combined outputs will then be used as inputs in the TIGCM for realistic time-dependent studies of the coupled thermosphere/ionosphere system. This technique is being developed for application to the upcoming NASA International Solar Terrestrial Physics/Global Geospace Science satellite missions where high resolution auroral airglow images will be obtained from the polar spacecraft.

Polar Wind

Holzer and Gerald Browning (Scientific Computing Division) have developed a new model of the polar wind. The "reduced" system of equations commonly used to describe the time evolution of the polar wind and multiconstituent stellar winds is derived from the complete equations for a multispecies plasma by assuming that the electron thermal speed approaches infinity. Browning and Holzer have shown that this reduced system is ill-posed near the proton sonic point for a significant range of physical parameters appropriate to the polar wind. The unmodified system (from which the reduced system is derived) is well-posed for this parameter range, although there is growth in some of the Fourier modes. An alternate system of equations (the "approximate" system), in which the electron thermal speed is slowed down (rather than speeded up to infinity), has thus been introduced by these authors. The approximate system retains the mathematical behavior of the unmodified system and accurately describes the smooth solutions of the unmodified system. An added advantage of the approximate system is that for three-dimensional flows it remains hyperbolic and only requires one-tenth as large a time step as that needed for the reduced system, which requires the solution of an elliptic equation for these flows.

Comparative Terrestrial Planet Thermospheres

Stephen Bougher (visitor, University of Arizona) and Roble have begun a study in which the thermospheres and characteristic structures of Venus, Earth, and Mars are compared and different physical and chemical processes are contrasted with each other. They recently completed a study of the solar cycle variations of the three planets using global mean models for each planet. The results show that the solar cycle global mean exospheric temperature variation is about 58 K for Venus (190 to 248 K), 518 K for Earth (737 to 1255 K), and 110 K for Mars (180 to 290 K). A thermal balance analysis showed that the small exospheric temperature variation on Venus occurs because of the strong radiative damping by CO_2–15 μm cooling. The increase in solar heating occurs at nearly the same altitude as the peak cooling, and therefore it is effectively radiated to space. On Earth, the increased solar heating occurs at a higher altitude than the peak in infrared cooling, and consequently it must be thermally conducted down to the altitude of the infrared cooling peak before it is radiated to space. An increase in molecular conduction requires an increase in the vertical temperature gradient which results in a larger exospheric temperature variation. On Mars, the increase in solar heating also occurs at a higher altitude than the peak cooling and likewise must be conducted downward before radiating to space. Furthermore, CO_2 cooling is not as effective on Mars as it is on Venus because of lower O/CO_2 ratios. These two factors result in a calculated Mars solar cycle variation of global mean temperatures that is larger than for Venus.

Bougher and Roble are now using the general circulation models of the three planets to examine the three-dimensional circulation differences. By studying the differences in the structure and circulation of the three planets and the role of CO_2 radiation as a cooling mechanism on each of the planets, they hope to better understand the effect of increasing CO_2 concentrations in the Earth's atmosphere.

Analysis of Clear-Air Radar Echoes

The behavior of clear-air radar echoes is far from being completely understood, and uncertainties in the determination of atmospheric winds from these echoes are large enough to cause significant problems for certain refined analyses of wind effects, such as for the measurement of momentum fluxes carried by gravity waves in the stratosphere. There is additional interest in knowing the relative merits of different radar configurations in order to optimize measurement capabilities and costs for both research and operational systems. Joel Van Baelen (HAO graduate research assistant) and Richmond designed and carried out spaced-receiver measurements of clear-air echoes at the middle and upper atmosphere (MU) radar in Japan, in collaboration with T. Tsuda, S. Kato, S. Fukao, M. Yamamoto (all of Kyoto University), and Susan Avery (University of Colorado), in order to compare different methods of wind determination and to analyze the structure of atmospheric refractive-index fluctuations that give rise to the echoes. They found that the standard full correlation analysis of spaced-antenna measurements yields "apparent" and "true" velocities that are both similar to the alternative Doppler beam swinging determinations of horizontal winds, but that the "true" velocities could underestimate the real wind amplitude if the spacing of receiving antennas is too small. Van Baelen and Richmond developed a third method, radar interferometry, as a way of examining in more detail the echoes as a function of Doppler frequency. They showed that in the absence of very strong specularity of the echoes, radar interferometry should produce reliable determinations of both the horizontal and vertical wind, automatically correcting the vertical wind determination for the important effects of off-vertical echo power. Van Baelen completed his Ph.D. thesis on these topics.

In a study by the same group, it was shown that echo power preferentially comes from a direction between the vertical and the normal to the three-dimensional wind vector. By using the thermal wind relation, they showed that, in the direction normal to the wind vector, echoes tend to come from a direction that is also normal to isentropic surfaces.

CEDAR Data Base

The CEDAR Data Base, managed by HAO, has continued to expand its holdings and services to the university community. Approximately 30 users of the database were served in FY 90. The UNIX Sun computer designed for database users was ordered in preparation for installation of the Millstone Hill database system in FY 91. Existing database codes were modified to work on the UNICOS CRAY and the planned UNIX Sun computer.

Among the in-house research with the database was a project by Laura Griffith (summer undergraduate student from Embry-Riddle Aeronautical University) to compare ionospheric data with model output from the TIGCM.

The database sponsored the 1990 Summer CEDAR Workshop, attended by 267 participants including 107 students. Emery was the local organizer. The meeting included 25 workshops, a poster session, and four tutorial lectures.

Staff and Visitors

Staff

Administrative and Research Support Section

Louise Beierle
Liz Boyd
Linda Croom
J.K. Emery
Thomas Holzer (director from 4/17/90)
Cindi Miller
Joan Morton
Janice Saffell
Kathryn Strand

Computing and Research Support Group

Peter Bandurian
Ray Bovet (manager)
Roy Barnes (50%)
Joan Burkepile
Carlye Calvin
Barbara Emery
Benjamin Foster
Thomas Hansford
Dan Haynes
Alice Lecinski
Rose Reynolds (to 7/13/90)
Cicely Ridley
William Roberts
Paul Seagraves
Linda Sirney (to 3/23/90)
Leonard Sitongia
Andrew Stanger
Kim Streander
Victor Tisone

Instrumentation Group

Greg Card
Clarke Chambellan (from 11/13/89)
David Elmore
Kristine Fisher
Charles Garcia, Jr.
Tom Gilbert
Howard Hull
Judd Johnson
Leon Lacey (to 8/14/90)
Terry Leach
Patricia Loudon
Ed Lundin (to 3/31/90)
Charlie Miller (to 6/1/90)
Paula Rubin
Christopher St. Cyr
Jeff Schuenke (manager)
Rick Sheffer
Eric Yasukawa

Solar Interior Section

Timothy Brown (section head)
Ronald Gilliland (to 11/14/89)
Pawan Kumar
Steve Tomczyk (from 7/1/90)

Coronal/Interplanetary Physics Section

Thomas Bogdan
Richard Fisher
Thomas Holzer (50%)
Arthur Hundhausen
Boon-Chye Low (sec. head) (act. dir. to 4/17/90)
Keith MacGregor (50%)
Victor Pizzo (50%)
Edward Shoub (50%)
David Sime

Solar Atmosphere and Magnetic Fields Section

Bruce Lites
Keith MacGregor (50%)
Victor Pizzo (50%)
Edward Shoub (50%)
Andrew Skumanich

Terrestrial Interactions Section

Thomas Holzer (50%)
Arthur Richmond
Raymond Roble (section head)

Affiliate Scientists

Jørgen Christensen-Dalsgård, University of Århus, Denmark
Timothy Killeen, University of Michigan
Egil Leer, Institute of Theoretical Astrophysics, University of Oslo, Norway
Dimitri Mihalas, University of Illinois
Robert Rosner, University of Chicago
John Thomas, University of Rochester

Graduate Research Assistants

Thomas Bida, University of New Mexico
Mihail Codrescu, Boston University (to 10/31/89)
Chris Halvorson, University of Colorado
Scott Horner, University of Chicago
Jesper Schou, University of Århus, Denmark
Joel Van Baelen, University of Colorado (to 8/31/90)

Visitors

Michelle Abboud, summer undergraduate student; Fairfield University; May 1990 to September 1990; Solar Atmosphere and Magnetic Fields Section

Tahar Amari; National Center for Scientific Research, Meudon, France; August 1990 to October 1990; Coronal/Interplanetary Physics Section

Grant Athay; unaffiliated; January 1989 to December 1992; Solar Atmosphere and Magnetic Fields Section

Stephen Bougher; University of Arizona; July 1990 to August 1990; Terrestrial Interactions Section

Jo Bruls; Utrecht Astronomy Institute, The Netherlands; September 1989 to November 1989; Solar Atmosphere and Magnetic Fields Section

Derek Buzasi; Pennsylvania State University; August 1989 to August 1990; Coronal/Interplanetary Physics Section

Matthias Bünte; Institute of Astronomy, Switzerland; November 1989 to March 1990;

Alessandro Cacciani; University of Rome, Italy; August 1990 to December 1990; Solar Interior Section

Paul Charbonneau; University of Montreal; August 1990 to August 1991; Coronal/Interplanetary Physics Section

Mihail Codrescu; Boston University; December 1989; Terrestrial Interactions Section

Paul Cohen, summer undergraduate student; Yale University; May 1990 to August 1990; Solar Atmosphere and Magnetic Fields Section

Geoffrey Crowley; University of Lowell; April 1990 and June 1990; Terrestrial Interactions Section

Rahim Esmailzadeh; Center for Particle Astrophysics; March 1990; Coronal/Interplanetary Physics Section

Katia Ferrierè; University of Colorado; September 1990 to September 1991; Coronal/Interplanetary Physics Section

Cassandra Fesen; Dartmouth College; July 1990 to August 1990; Terrestrial Interactions Section

Jeffrey Forbes; Boston University; August 1990 to July 1991; Terrestrial Interactions Section

Sarah Gibson; University of Colorado; January 1990 to June 1990; Coronal/Interplanetary Physics Section

Laura Griffith, summer undergraduate student; Embry-Riddle Aeronautical University; May 1990 to August 1990; Terrestrial Interactions Section

Maura Hagan; Massachusetts Institute of Technology, Haystack Observatory; August 1990 to July 1991; Terrestrial Interactions Section

Viggo Hansteen; Institute of Theoretical Astrophysics, University of Oslo, Norway; July 1990 to August 1990; Coronal/Interplanetary Physics Section

Julia Hargreaves, summer undergraduate student; Queen's College, Oxford, England; June 1990 to September 1990; Coronal/Interplanetary Physics Section

Paul Hays; University of Michigan; September 1989 to May 1990; Terrestrial Interactions Section

Ivan Hubeny; University of Vienna, Austria; July 1988 to July 1990; Coronal/Interplanetary Physics Section

Stephen Kahler; NOAA; September 1989 to April 1990; Coronal/Interplanetary Physics Section

Michael Knölker; Kiepenheuer-Institute for Solar Physics, Germany; August 1990 to September 1990; Coronal/Interplanetary Physics Section

Bob Lee; unaffiliated; April 1989 to September 1992; Coronal/Interplanetary Physics Section

Jean Lilensten; Center for the Study of Random Geophysical Phenomena/Grenoble National Technical School for Electrical Engineers, France; September 1989 to September 1990; Terrestrial Interactions Section

Edward Lu; Stanford University; October 1989 to October 1991; Coronal/Interplanetary Physics Section

Dirk Lummerzheim; University of Alaska; September 1989 to December 1990; Terrestrial Interactions Section

Sandy McClymont; University of Hawaii; September 1990; Solar Atmosphere and Magnetic Fields Section

Bob MacQueen; NCAR (sabbatical); July 1989 to June 1990; Coronal/Interplanetary Physics Section

Barbara Mihalas; University of Illinois; June 1990 to August 1990; Solar Interior Section

Cherilynn Morrow; Cambridge University, England; August 1989 to November 1989; Solar Interior Section

Julie Moses; The Aerospace Corporation; July 1988 to September 1990; Terrestrial Interactions Section

Stanley Owocki; Bartol Research Institute; July 1990 to August 1990; Coronal/Interplantary Physics Section

Dieter Schmitt; University Observatory, Göttingen, Germany; September 1989 to August 1990; Solar Atmosphere and Magnetic Fields Section

Jacqueline Schoendorf; University of Lowell; June 1990; Terrestrial Interactions Section

Neil Sheeley; Naval Research Laboratory; November 1989; Coronal/Interplanetary Physics Section

Stanley Solomon; University of Michigan; September 1987 to December 1989; Terrestrial Interactions Section

Richard Steinolfson; Southwest Research Institute; October 1989 to January 1990 and May 1990 to June 1990; Coronal/Interplanetary Physics Section

Peter Stoltz; University of California, Berkeley; March 1990 to August 1989; Solar Atmosphere and Magnetic Fields Section

Jim Stone; University of Illinois; July 1990 to August 1990; Coronal/Interplanetary Physics Section

John Streete; Rhodes College; May 1990 to July 1990; Coronal/Interplanetary Physics Section

Christopher Taylor; Harvard College; June 1990 to September 1990; Computing and Research Support Group

Michael Thompson; Århus University, Denmark; August 1988 to December 1989; Solar Interior Section

Steven Tomczyk; Mount Wilson Observatory; June 1988 to June 1990; Solar Interior Section

Haruichi Washimi; Nagoya University, Japan; September 1990 to October 1990; Coronal/Interplanetary Physics Section

Tod Woods; Princeton University; September 1989 to October 1989; Coronal/Interplanetary Physics Section

Publications

Refereed Publications

ANDERSON, L.S., and R.G. ATHAY, 1989: Model solar chromosphere with prescribed heating. *Astrophys. J.* **346**, 1010-1018.

ATHAY, R.G., 1990: CIV plasma flow near active region filaments. *Solar Phys.* **126**, 135-152.

——, and *K.P. Dere, 1990: Bifurcation in the low chromosphere. *Astrophys. J.* **358**, 710-717.

——, and *——, 1989: Temperature and center-limb variations of transition region velocities. *Astrophys. J.* **346**, 514-522.

*BERKEY, J.E., A.D. RICHMOND, *R.M. BARNES, *S. GONZALEZ, and *C.A. TEPLEY, 1990: Solar cycle variations in F region electrodynamic drifts at Arecibo. *J. Geophys. Res.* **95** (A4), 4303-4306.

BOGDAN, T.J., 1989: On the resonance scattering of sound by slender magnetic flux tubes. *Astrophys. J.* **345**, 1042-1049.

BROWN, T.M., 1990: An inverse method for p-mode scattering measurements. *Sol. Phys.*, **128**, 133-141.

——, and J. CHRISTENSEN-DALSGÅRD, 1990: A technique for estimating complicated power spectra from time series with gaps. *Astrophys. J.* **349**, 667-674.

——, and *R.L. GILLILAND, 1990: A search for solar-like oscillations in Alpha Centauri A. *Astrophys. J.* **350**, 839-845.

*BURNS, A.G., T.L. KILLEEN, G. CROWLEY, B.A. EMERY, and R.G. ROBLE, 1989: On the mechanisms responsible for high-latitude thermospheric composition variations during the recovery phase of a geomagnetic storm. *J. Geophys. Res.* **94** (A12), 16,961-16,968.

*CARLSON, H.C., and G. CROWLEY, 1989: The equinox transition study: An overview. *J. Geophys. Res.* **94** (A12), 16,861-16,868.

CHRISTENSEN-DALSGÅRD, J., J. SCHOU, and M.J. THOMPSON, 1990: A comparison of methods for inverting helioseismic data. *Mon. Not. R. Astr. Soc.* **242**, 353-369.

CODRESCU, M., J.M. FORBES, and R.G. ROBLE, 1990: Thermospheric dynamics: A system theory approach. *Radio Science* **25** (4), 299-308.

CROWLEY, G., B.A. EMERY, R.G. ROBLE, *H.C. CARLSON, JR., D.J. KNIPP, 1989: Thermospheric dynamics during September 18-19, 1984. 1. Model simulations. *J. Geophys. Res.* **94** (A12), 16,925-16,944.

——, ——, ——, *——, *J.E. SALAH, *V.B. WICKWAR, *K.L. MILLER, *W.L. OLIVER, *R.G. BURNSIDE, and *F.A. MARCOS, 1989: Thermospheric dynamics during September 18-19, 1984. 2. Validation of the NCAR Thermospheric General Circulation Model. *J. Geophys. Res.* **94** (A12), 16,945-16,959.

EMERY, B.A., A.D. RICHMOND, *H.W. KROEHL, *C.D. WELLS, *J.M. RUOHONIEMI, *M. LESTER, D.J. KNIPP, *F.J. RICH, *J.C. FOSTER, *O. de la BEAUJARDIERE, *C. SENIOR, *L.M. SHIER, *J.F. MCKEE, and *S. MAEDA, 1990: Electric potential patterns deduced for the SUNDIAL period of September 23-26, 1986. *Annales Geophysicae* **8** (6), 399-408.

FORBES, J.M., and R.G. ROBLE, 1990: Thermosphere-ionosphere coupling: An experiment in interactive modeling. *J. Geophys. Res.* **95** (A1), 201-208.

*GOLDREICH, P., and P. KUMAR, 1990: Wave generation by turbulent convection. *Astrophys. J.* **363**, 694-704.

GOODMAN, M.L., 1990: Alfvén-type wave motion induced by the Hall effect. *Phys. Fluids B* **1** (12), 2305-2307.

*HAMILTON, R.J., E.T. LU, and *V. PETROSIAN, 1990: Numerical solution of the time-dependent kinetic equation for electrons in magnetized plasma. *Astrophys. J.* **354**, 726-734.

*——, and D.G. SIME, 1989: The launch of coronal mass ejections: White light and X Ray observations in the low corona. *J. Geophys. Res.* **94** (A3), 2333-2344.

*HARRISON, R.A., *E. HILDNER, A.J. HUNDHAUSEN, D.G. SIME, and *G.M. SIMNETT, 1990: The launch of solar coronal mass ejections: Results from the coronal mass ejection onset program. *J. Geophys. Res.* **95** (A2), 917-937.

*HASSLER, D.M., *G.J. ROTTMAN, E.C. SHOUB, and T.E. HOLZER, 1990: Line broadening of Mg x $\lambda\lambda$609 and 625 coronal emission lines observed above the solar limb. *Astrophys. J.*, **348**, L77-L80.

*HU, Y.Q., *Z. ZHONG-WEI, A.J. HUNDHAUSEN, T.E. HOLZER, and B.C. LOW, 1990: Slow shocks in an open magnetic field near the sun. *Science in China* **33** (3), 332-344.

*——, *——, ——, ——, and ——, 1990: Numerical modeling of slow shocks in an open magnetic field near the sun. *Scientia Sinica*, **33**, 332-344.

*——, *——, ——, ——, and ——, 1990: Slow MHD shocks in the open magnetic fields near the sun (translated title). *Scientia Sinica* **33**, (3), 332-344.

HUBENY, I., 1990: Vertical structue of accretion disks: A simplified analytical model. *Astrophys. J.* **351**, 632-641.

KNIPP, D.J., A.D. RICHMOND, G. CROWLEY, *O. de la BEAUJARDIÈRE, *E. FRIIS-CHRISTENSEN, *D.S. EVANS, *J.C. FOSTER, *I.W. MCCREA, *F.J. RICH, and *J.A. WALDOCK, 1989: Electrodynamic patterns for September 19, 1984. *J. Geophys. Res.* **94** (A12), 16,913-16,923.

LEER, E., and T.E. HOLZER, 1990: Standing shocks in the inner solar wind. *Astrophys. J.* **358**, 680-684.

LITES, B.W., *G.B. SCHARMER, and A. SKUMANICH, 1990: High-resolution spectra of solar magnetic features. I. Analysis of penumbral fine structure. *Astrophys. J.* **355**, 329-341.

——, and A. SKUMANICH, 1990: Stokes profile analysis and vector magnetic fields. V. The magnetic field structure of large sunspots observed with Stokes II. *Astrophys. J.* **348**, 747-760.

LOU, Y.Q., 1989: The onset of magnetohydrodynamic convective instability. I. Ideal limit. *Astrophys. J.* **347**, 520-528.

——, 1990: Viscous magnetohydrodynamic modes and p-mode absorption by sunspots. *Astrophys. J.* **350**, 452-462.

LOW, B.C., 1990: Equilibrium and dynamics of coronal magnetic fields. *Annu. Rev. Astron. Astrophys.* **28**, 491-524.

——, and Y.Q. LOU, 1990: Modeling solar force-free magnetic fields. *Astrophys. J.* **352**, 343-352.

LU, E.T., and *V. PETROSIAN, 1990: The relative timing of microwaves and X-rays from solar flares. *Astrophys. J.* **354**, 735-744.

LUMMERZHEIM, D., *M.H. REES, and *G.J. ROMICK, 1990: The application of spectroscopic studies of the aurora to thermospheric neutral composition. *Planetary and Space Science* **38** (1), 67-78.

MIHALAS, D., *D.G. HUMMER, B. MIHALAS, and *W. DAPPEN, 1990: The equation of state for stellar envelopes. IV. Thermodynamic quantities and selected ionization fractions for six elemental mixes. *Astrophys. J.* **350**, 300-308.

*MIHALOV, J.D., *A. BARNES, A.J. HUNDHAUSEN, and *E.J. SMITH, 1990: Solar wind and coronal structure near sunspot minimum: Pioneer and SMM observations from 1985-1987. *J. Geophys. Res.* **95** (A6), 8231-8242.

*ORRALL, F.Q., *G.J. ROTTMAN, R.R. FISHER, and *R.H. MUNRO, 1990: The solar coronal density irregularity $\overline{n^2}/(\overline{n})^2$ derived from simultaneous measurments of the EUV and K-coronal brightness. *Astrophys. J.* **349**, 656-666.

POE, C.H., S.P. OWOCKI, and *J.I. CASTOR, 1990: The steady state solutions of radiatively driven stellar winds for a non-Sobolev, pur absorption model. *Astrophys. J.* **358**, 199-213.

*RHODES, JR., E.J., A. CACCIANI, *S.K. KORZENNIK, S. TOMCZYK, *R.K. ULRICH, and *M.F. WOODARD. 1990: Depth and latitude dependence of the solar internal angular velocity. *Astrophys. J.* **351**, 687-700.

RICHMOND, A.D., *Y. KAMIDE, *S.-I. AKASOFU, *D. ALCAYDÉ, *M. BLANC, *O. de la BEAUDARDIERE, *D.S. EVANS, *J.C. FOSTER, *E. FRIIS-CHRISTENSEN, *J.M. HOLT, *R.J. PELLINEN, *C. SENIOR, and *A.N. ZAITZEV, 1990: Global measures of ionospheric electrodynamic activity inferred from combined incoherent scatter radar and ground magnetometer observations. *J. Geophys. Res.* **95** (A2), 1061-1071.

ROBLE, R.G., and *R.E. DICKINSON, 1989: How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophys. Res. Letts.* **16** (12), 1441-1444.

ROSNER, R., B.C. LOW, *K. TSINGANOS, and *M.A. BERGER, 1989: On the relationship between the topology of magnetic field lines and flux surfaces. *Geophys. Astrophys. Fluid Dynamics* **48**, 251-271.

*SCHNEIDER, P., and T.J. BOGDAN, 1989: Energetic particle acceleration in spherically symmetric accretion flows: importance of a momentum-dependent diffusion coefficient. *Astrophys. J.* **347**, 496-504.

SIME, D.G., and *M.K. MCCABE, 1990: The structure of the white-light corona and the large-scale solar magnetic field. *Solar Phys.* **126**, 267-284.

SOLOMON, S.C., 1989: Auroral excitation of the N2 2P(0,0) and VK(0,9) bands. *J. Geophys. Res.* **94** (A12), 17,215-17,222.

STEINOLFSON. R.S., and A.J. HUNDHAUSEN, 1990: Concave-outward slow shocks in coronal mass ejections. *J. Geophys. Res.* **95**, (A9), 15,251-15,256.

——, and ——, 1990: MHD Intermediate shocks in coronal mass ejections. *J. Geophys. Res.* **95**, (A5), 6389-6401.

THOMPSON, M., 1990: A new inversion of solar rotational splitting data. *Solar Physics* **125**, 1-12.

VAN BAELEN, J.S., *T. TSUDA, A.D. RICHMOND, *S.K. AVERY, *S. KATO, *S. FUKAO, and *M. YAMAMOTO, 1990: Comparison of VHF Doppler beam swinging and spaced antenna observations with the MU radar: First results. *Radio Science* **25** (4), 629-640.

WOODS, D.T., T.E. HOLZER, and K.B. MACGREGOR, 1990: Lower solar chromosphere-corona transition region. I. Theoretical models with small temperature gradients. *Astrphys. J.* **355**, 295-308.

——, ——, ——, 1990: Lower solar chromosphere-corona transition region. II. Wave pressure effects for a specific form of the heating function. *Astrophys. J. Suppl. Series* **73**, 489-512.

——, ——, ——, 1990: Lower solar chromosphere-corona transition region. III. Implications of the observed quiet-sun emission measure including wave pressure effects. *Astrphys. J.* **355**, 309-320.

*YOUNG, A., A. SKUMANICH, K.B. MACGREGOR, and *S. TEMPLE, 1990: High-latitude spot and plage activity on the rapidly rotating M dwarf star Gliese 890. *Astrophys. J.* **349**, 608-619.

Other Publications

BROWN, T.M., 1990: High precision doppler measurements via echelle spectroscopy. In *CCD_3 in Astronomy*, (G. Jacoby, ed.), Astronomical Society of the Pacific Conference Series **8**, 335-344.

HUNDHAUSEN, A.J., D.G. SIME, and B.C. LOW, 1990: Solar corona mass ejections, in *Galactic and Intergalactic Magnetic Fields*, Proceedings of the 140th IAU Symposium (R. Beck, *et al.*, eds.), Kluwer Academic Publishers, 16.

*LEE, M.A., T.J. BOGDAN, and *P. SCHNEIDER, 1990: Coupled stochastic Fermi acceleration and wave damping in space plasmas. In *Proc. 21st Int. Cosmic Ray Conf.*, **5**, 348-351.

LOW, B.C., 1990: Magnetic free-energy in the solar atmosphere. In *Proc. 1988 Yosemite Conf.*, American Geophysical Union, 21-29.

——, 1990: The dynamics of solar coronal magnetic fields, in *Galactic and Intergalactic Magnetic Fields*, Proceedings of the 140th IAU Symposium (R. Beck, *et al.*, eds.), Kluwer Academic Publishers, 13-15.

——, 1990: Spontaneous formation of electric current sheets in astrophysical magnetic fields. In *Proc. IUTAM Symposium on Topological Fluid Mechanics*, (H.K. Moffatt and A. Tsinober, eds.), Cambridge Universtiy Press, 235-243.

ROBLE, R.G., 1990: Book review of Special CEDAR issues of the *Journal of Atmospheric and Terrestrial Physics. Planet. Space Sci.* **38**, 701-702.

* An asterisk denotes a non-NCAR author.

NCAR Annual Scientific Report Fiscal Year 1990 - Link Page

Next PART0002

National Center for Atmospheric Research
Annual Scientific Report
Fiscal Year 1990

Submitted to National Science Foundation
by
University Corporation for Atmospheric Research
June 1991

Mesoscale and Microscale Meteorology Division

The research program of the Mesoscale and Microscale Meteorology (MMM) Division is directed towards understanding atmospheric phenomena on space scales of millimeters to a megameter, on time scales of seconds to a day. The research activities are devoted to the study of (1) the physical mechanisms that govern the behavior of mesoscale weather systems and the factors that determine their predictability; (2) the basic nature of moist atmospheric convection, its interaction with topography and other lower boundary effects, and how cloud and precipitation microphysics and large-scale dynamical factors influence its behavior; and (3) the fundamental atmospheric processes that operate on scales of up to a few kilometers, including boundary-layer processes, turbulence, and cloud and precipitation microphysics.

The MMM scientific program combines theoretical and laboratory work, numerical model development and experimentation, and design, coordination, and conduct of major field experiments. This scientific program complements and extends university-based research through vigorous scientific visitor support, collaboration in field work, and community use of major modeling, data analysis, and display systems which are developed and maintained by the division.

Division Organization

The division is organized into three sections: Mesoscale Prediction, Convective Meteorology, and Microscale Meteorology. The principal focus of research within each of these sections corresponds, respectively, to the three areas mentioned above. The division is also the administrative home for NCAR's Office of Field Project Support (OFPS), which provides an NCAR/NSF focal point for interagency and international field project planning and implementation.

Significant Accomplishments

- Large-eddy simulations have shown how radiative cooling generates turbulence in cloud-topped mixed layers, which has important implications for the dissipation of stratiform clouds through the entrainment of warm dry air from above.

- Observational studies using First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE) aircraft data have revealed that horizontal inhomogeneity in marine stratiform cloud regimes is commonly observed and has a significant effect on cloud formation and dissipation.

- Measured changes in the size spectra of sulfuric acid droplets in the arctic stratosphere indicate, contrary to previous assumptions, that the majority of the droplets are supercooled at the temperature at which polar stratospheric clouds could begin to form but that they freeze homogeneously at slightly colder temperatures. This observation alters our view of the mechanisms important in the formation of polar stratospheric clouds that are directly involved in polar ozone loss.

- High-resolution mesoscale model simulations have reproduced the remarkable structure of recently documented warm-core marine cyclones that are in contradiction to the classical Norwegian cyclone model.

- Studies of bow echoes and downbursts have been completed that identify the mechanisms producing these significant storm features.

- Initiation of convection along the Colorado Front Range in the presence of southerly flow has been shown to occur through complex nonlinear interactions involving boundary-layer instabilities, tropospheric gravity waves, and nocturnal low-Froude-number flow effects.

- Momentum transport by organized convection in both idealized models and the real atmosphere has been represented by a comprehensive nonlinear theory and applied to represent momentum transport in general circulation models.

- Entrainment and mixing along the interface between the cloud and its environment have been shown to occur through convective and shearing instabilities and vorticity generation.

- Techniques have been developed to assimilate precipitable water measurements into a mesoscale model. The assimilation of precipitable water produces a much better estimate of the vertical structure of water vapor than statistical methods based on climatology, and improves the precipitation forecast of the model.

- A nonhydrostatic, compressible adaptive-grid model has been developed that can automatically place and move fine-grid regions based on estimates of truncation errors in the numerical solution.

- OFPS made major contributions to preparation of the draft U.S. Weather Research Program plan for the Mesoscale Working Team of the Committee on Earth and Environmental Sciences' Subcommittee on Atmospheric Research, and to the experiment design plan for the Stormscale Operational and Research

Meteorology (STORM) Fronts Experiment Systems Test. OFPS established a STORM Data Management Center function including Unidata distribution of hourly wind profiler data.

- The MMM Division was major contributor to the planning and execution of the Hawaiian Rainband Project (HaRP) which took place during July and August 1990, and involved over 50 scientists from NCAR and the university community. Observations focused on the initiation, structure, and variability of rainbands on the windward side of Hawaii and mesoscale vortices in the lee. MMM numerical models were run in real time to assist the planning and execution of the field experiments.

- MMM scientists participated in the Winter Icing and Storms Project (WISP), conducted during the winter of 1989–90, which provided good documentation of the precipitation processes and ice concentrations in winter storms of eastern Colorado.

- The MMM Division, together with the Advanced Study Program (ASP) and NOAA's Forecast Systems Laboratory (FSL), coordinated the NCAR Summer Colloquium on Four-Dimensional Data Assimilation which took place during 6 June–3 July 1990, in which 55 students and 23 lecturers from 15 different countries participated. The division also organized the Workshop on TAMEX (Taiwan Area Mesoscale Experiment) Scientific Results and the U.S./People's Republic of China (PRC) Workshop on Mesoscale Meteorology.

Fronts and Cyclones

Potential-Vorticity Anomalies in Upper-Level Jets

Daniel Keyser (State University of New York at Albany) and Richard Rotunno have reviewed and discussed a long-standing difference in interpretation of the role of turbulence in modifying the potential-vorticity distribution in the vicinity of upper-level jet-front systems. In the late 1970s, Melvyn Shapiro (NOAA) presented observational evidence that turbulent mixing of heat can result in a positive anomaly of the Ertel potential vorticity on the cyclonic-shear side of upper-level jets near the level of maximum wind. Edwin Danielsen (retired) and collaborators disputed this evidence and the accompanying interpretation, arguing that turbulent mixing of potential vorticity is downgradient, and so, cannot produce anomalies from initially smooth distributions of potential vorticity. Keyser and Rotunno resolve the dispute as follows: Shapiro defined potential vorticity as the scalar product of the averaged absolute vorticity and the averaged potential-temperature gradient, whereas Danielsen et al. defined it as the average of the scalar product of these quantities. They concluded that the positive anomaly of potential vorticity identified by Shapiro is plausible if one accepts his definition of potential vorticity. Moreover, they point out that Shapiro's alternative is the only practical option when working with observed or simulated data. Finally they reason that since downgradient diffusion of potential vorticity is dubious, Danielsen's alternative framework is not viable, even if one could directly measure his version of potential vorticity.

Narrow Cold-Frontal Rainbands

David Parsons has used a numerical model to investigate the dynamics of narrow cold-frontal rainbands (NCFRs). Parsons simulated the intense frontal rainband observed along a cold front in central California on 5 February 1978 in which vertical motions exceeded 15 m/s in a narrow line (km-scale) along the leading edge of the cold front despite a lack of appreciable potential instability within the inflow. His simulations with the ambient vertical shear replicated the intense updraft and narrow band of precipitation evident in the observations. As expected from the lack of potential instability, the intense vertical accelerations in both his simulations and observations were forced by the vertical pressure gradients. In order to understand the factors that control this force, Parsons used simulations with idealized conditions, and his findings are in agreement with observations that show NCFRs are commonly observed when the air ahead of the front has a deep (on the order of 3 km) layer that is nearly saturated, moist adiabatic, and a wind profile that has intense vertical shear in the lowest 1 to 2 km.

The above simulations were initialized with the cold air mass approximated by a gravity current. Parsons believes the striking agreement between the observations and the simulations is further evidence that frontal flows on this scale are well approximated by the gravity-current model. Parsons finds, however, that differences exist between the frontal flow associated with NCFRs and that predicted by classical gravity current theory due to the inclusion of vertical shear and precipitation. He finds that the increase in the depth and strength of the updraft at the leading edge of the gravity current with increasing low-level shear is consistent with the theory proposed by Rotunno, Joseph Klemp, and Morris Weisman. However, for large vertical shears, and deep shear layers, the circulations within the cold pool become increasingly different from the theoretical ones. Also, he finds that the heavy rainfall associated with the NCFR in this case produces a flow within the cold air mass that is reversed from the flow observed in dry gravity currents.

Another feature of NCFRs is the distinct presence of along-front disturbances with mesoscale wavelengths (typically 10–100 km). Parsons is working with John Clark (visitor, Pennsylvania State University) in an effort to understand further these disturbances, which can sometimes result in mesocyclones and even tornadoes being produced. They have used three-dimensional simulations of gravity current flows with realistic initial conditions and have simulated the observed features of these mesoscale disturbances, including the alternating presence of mesocyclones and strong cores of vertical motion along the front. Current work is concentrating on examining the creation of vorticity within these cyclones and on improving the understanding of the mechanisms responsible for the formation of these waves.

Dryline Fronts

The dryline is a moisture front in the south central United States dividing warm moist air that has moved over the Gulf of Mexico from hot dry air characteristic of the high inland plateau of the southwestern United States. During the spring and early summer, this boundary is the predominant initiator of convective events over large areas of West Texas and Oklahoma. Parsons, Michael Hardesty, and Shapiro (both of NOAA's Wave Propagation Laboratory) have completed a study of the dynamics of the dryline. This study employed a Doppler lidar to measure the air motions associated with the dryline prior to the outbreak of convection. Measurements on scales comparable to the dryline gradients were previously lacking. They found strong ($\sim$5 m/s^1) vertical motions at the dryline interface. The local density differences across the dryline, downplayed in many previous studies of the dryline, are responsible for strong convergence at the dryline interface and play a role in the movement of the dryline interface. The study is one of the more novel and detailed uses of Doppler lidar to date.

Thermal Structure of a Simulated Marine Cyclone

Aircraft observations of marine cyclones have only recently documented the mesoscale frontal structures associated with these storms. In particular, during the mature phase of the cyclones, polar air almost completely encircles the storm center, secluding a mesoscale ($\approx$100 km) warm pocket of air near the center at a level $\approx$300 m above the surface. Temperatures within the seclusion are 5–10^{o}C warmer than those on the cold side of the encircling front. This feature is not included in the description of the occlusion process in the Norwegian cyclone model. Ying-Hwa Kuo and Simon Low-Nam, in collaboration with Richard Reed (visitor, University of Washington), have conducted high-resolution (20-km grid spacing) simulations of an explosive cyclone over the western Atlantic using the Pennsylvania State University/ NCAR mesoscale model, MM4. The model simulated the seclusion process found by the aircraft observations. Their analysis of these simulations shows: (1) during the mature phase the warm-core structure extended from near the surface to 500 mb; (2) the 900-mb secluded warm air originated from near the surface within the broad baroclinic zone to the east of the cyclone while the storm was still in an open-wave stage, and this air did not originate from the warm sector of the cyclone; and (3) the storm-relative trajectories indicate that the seclusion process is a consequence of the kinematics of the developing cyclone.

Predictability of Explosive Cyclogenesis

During the Experiment on Rapidly Intensifying Cyclones and Anticyclones (ERICA) field project, the medium-range forecast models at the National Meteorological Center (NMC) predicted a number of explosive cyclones with a high degree of accuracy and consistency several days in advance, suggesting that these cyclogenesis events are highly predictable. On the other hand, detailed case studies have often found that the success of a numerical simulation of explosive cyclogenesis strongly depends on the quality of the initial conditions. These conflicting results raise questions concerning the predictability of explosive cyclones. Kuo and Low-Nam conducted a predictability study on an intense marine cyclone observed during ERICA using both a hemispheric and a regional version of MM4. Their time-lag forecasts using the hemispheric MM4 show that there is a significant degradation of forecast skill as the forecast duration is increased. This is reflected in the predicted 24-h pressure fall, the onset of rapid deepening, and the position of the predicted storms. The rapid decrease of forecast skill gives an indication of the low predictability of explosive cyclogenesis. Their results show that the predictability of error growth over a region of explosive cyclogenesis is much larger than that of ordinary flow at midlatitudes. The error growth is also larger than that of an ordinary cyclone. The difference is particularly marked in the lower troposphere. In summary, these preliminary results indicate that both the medium-range and short-range predictions of explosive cyclogenesis are highly sensitive to uncertainties in the initial conditions. The optimistic results from the medium-range model forecasts are somewhat misleading, because these forecasts are only evaluated on a synoptic scale in time and space. Considerably more work is needed to refine the conclusions obtained here.

Mesoscale Variation of Sea Surface Temperature

Satellite observations of warm ocean currents (such as the Gulf Stream) often display an extremely strong lateral variation in sea surface temperature (SST). Also, the warm ocean eddies are embedded within the current. These mesoscale ocean features result in strong mesoscale variation in the SST, which is normally unresolved in the operational numerical weather prediction models. Since rapid marine cyclogenesis is sensitive to surface energy fluxes, the mesoscale structure of SST may be important to marine cyclogenesis. In an effort to determine the impact of mesoscale SST variations, Low-Nam and Kuo conducted a series of numerical simulations on a case of East Coast cyclogenesis using the MM4 model with two kinds of SST analysis. The first is the smooth NMC 2.5° global SST analysis, and the other is a manual analysis of ship SST observations with considerable mesoscale detail. They found that strong SST gradients result in stronger precipitation and more intense deepening during portions of cyclone's life time. However, they also found that the different SST analyses have only small influences on the pressure decrease over a 24-h period. They believe that for the development of marine cyclones, the total amount of surface energy fluxes is more important than their mesoscale distribution.

Cyclogenesis Climatology

Shou-Jun Chen (long-term visitor, Beijing University, PRC) and Kuo conducted a synoptic climatological analysis of cyclogenesis over East Asia and the adjacent northwestern Pacific for the period 1958–87 based on the Beijing Meteorological Center's historical surface maps. They found that the most active cyclogenetic areas were: (1) the lee sides of the Altai-Sayan, Stanovoi, and Great Xinganling mountains, and (2) the East China Sea and the Sea of Japan. They believe that the former was related to lee cyclogenesis and the latter to coastal cyclogenesis. The Altai-Sayan lee cyclogenesis occurred in a manner very similar to that of Alpine lee cyclogenesis, which is related to the interaction of a propagating baroclinic wave and the regional-scale orography.

Primitive-Equation vs. Semigeostrophic Model

William Skamarock, Rotunno, and Klemp have adapted the Klemp-Wilhelmson cloud model to run efficiently for large domains. Preliminary to implementing moving nested grids to resolve the dry frontal evolution, Skamarock and Rotunno, along with Christopher Snyder (ASP postdoctoral fellow), have made direct comparisons between simulations using the cloud model and previously published solutions of baroclinic waves and frontogenesis using semigeostrophic (SG) models. In contrast to previous tests of SG theory against primitive-equation models in two-dimensional problems, where SG treatment is quite successful, these comparisons have revealed that SG models make significant errors in simulations of three-dimensional baroclinic waves, both in the large-scale wind and pressure fields, and in the location and intensity of fronts. Asymptotic analysis of the SG equations for small Rossby number suggests that the errors in the equations arise from their neglect of the dynamical contributions of the ageostrophic vorticity. Snyder, Skamarock, and Rotunno have shown that this is indeed the case by deriving and solving an extended equation set that includes the leading-order contributions of the ageostrophic vorticity.

Gravity Currents

Klemp, Rotunno, and Skamarock have continued to investigate the fundamental properties of gravity currents, using idealized theoretical models along with numerical models to refine the understanding of their structure and propagation. Two-dimensional gravity-current simulations of the dam-break problem have revealed that the formula derived by Benjamin in 1968 provides a good estimate of the gravity-current propagation. Including surface friction reduces the propagation speed as it produces dissipation within the cold pool. They also examined the characteristics of gravity currents using shallow-water theory, and their results suggest that energy-conserving solutions may, in fact, be unrealizable. In situations where the source of cold air remains fixed relative to the leading edge of the gravity current, solutions confirm that propagation speeds in excess of Benjamin's estimate are possible.

Tropical Storm ISABEL (1985)

Gary Barnes and Gregory Stossmeister have completed their analysis of 44 radial passes made by the two NOAA WP-3P3 aircraft over a three-day period in Tropical Storm Isabel, which did not achieve hurricane intensity. Barnes and Stossmeister find that: (1) a new circulation forms in response to intensifying convection in a rainband located near the radius of maximum winds; (2) this new circulation becomes the center for the entire tropical storm; (3) the new center is not located in the cumulonimbi of the rainband but instead is found under the downwind anvil; and (4) the new center is associated with warm, dry air and low equivalent potential temperature. Their findings suggest that radical changes in the apparent circulation center are likely due to the creation of a new warm core rather than erratic changes in the motion of the original warm column.

Barnes and Stossmeister have developed the hypothesis that strong unsaturated downdrafts from the anvil portion of a mesoscale convective system (MCS), if sustained over a horizontal extent of 30–40 km, can produce a region of low pressure hydrostatically that contributes to the genesis process. They argue that for most MCSs that fail to develop an incipient low-level circulation despite favorable climatology, the horizontal scale of the pressure deficit is too small, the column is too quickly sheared away, or the subsidence is not sustained for the period necessary to serve as the mesolow seed for the tropical cyclone.

Equatorial Mesoscale Experiment (EMEX)

During the EMEX, the NOAA WP-3D, the NCAR Electra, and the Australian F-27 probed a rainband in developing Tropical Cyclone Irma (1987). Barnes, Edward Zipser (visitor, Texas A&M University), and Brian Ryan (Commonwealth Scientific and Industrial Research Organization or CSIRO, Aspendale, Victoria, Australia) have completed their analysis of this rainband using data from these aircraft as well as radar and rawinsondes from nearby land stations. To date there have been no observations on rainbands during tropical cyclone development to learn whether the band helps or hinders the development process.

They find that (1) the intense convective cells do not organize into well-defined, long-lived lines; (2) their locus defines the mesoscale band location and motion systematically over several hours; (3) stratiform precipitation is intermingled with the convective cells with the fractional coverage of stratiform rain increasing down the band; (4) downdrafts are only slightly cooler than the environment and discontinuous; and (5) only a small fraction of the rain-cooled air has equivalent potential temperatures θ_e low enough to indicate descent from above 1 km. Their kinematic analyses reveal that (6) the air in the lowest 5 km converges into the band from both sides and flows down the band, (7) the convergence of the normal component of the wind is spread over a 40–50 km width, and (8) there is a marked parallel wind component maximum between 1000 and 1500 m occupying the outer half of the band.

This rainband differs from other convectively active bands that were studied in Hurricanes Floyd (1981) and Earl (1986) in that low-level flow does not pass through the band at a large crossing angle. Instead, the flow becomes more parallel to the band in Irma. Barnes, Zipser, and Ryan hypothesize that the environment is so moist as to limit cold-downdraft production and large decreases in θ_e. The net result of the band is to make the flow more tangential, but without substantially reducing the energy of the inflow. This results in a longer trajectory for the inflow, and at a higher speed that would favor larger energy transfers from the sea to the air. They hypothesize that a rainband of this type would have a tendency to enhance tropical cyclone intensification.

Mesoscale Convective Systems

Squall Lines

Stanley Trier and Parsons collaborated with Clark in completing a study of the evolution and internal precipitation structure of an MCS associated with a cold front observed on 26–27 June 1985 during the Preliminary Regional Experiment for STORM (PRE-STORM). The conditions ahead of this MCS included very weak line-normal vertical shear, abundant potential instability, and little convective inhibition. The system was long-lived, lasting ~16 h, and was one of the most prolific rainfall producers observed during PRE-STORM. The latter characteristics are somewhat surprising since many previous observational and numerical studies have suggested that moderate line-normal vertical shear was necessary to produce an intense, long-lived squall line. While these recent studies have focused on the interaction of the line-normal vertical shear with the gust front in maintaining the convective activity, Trier and his colleagues found that the convection in this MCS was aided by a component of discrete propagation, resulting from the formation of deep convection well in advance of any well-defined storm gust front.

Trier, Parsons, and Clark also found that a lack of appreciable convective inhibition in the presence of surface heating and mesoscale upward motion explains the triggering of convection ahead of the gust front. Their result showing the presence of convection ahead of the MCS, is similar to the behavior of some oceanic tropical and subtropical squall lines, although in this case moderate shear in the along-line direction organized the presquall convection into cloud streets which later evolved into nearly stationary lines of deep convection. These nearly stationary presquall lines, containing cells moving with the mean wind along their axis, partly account for the heavy rainfall associated with the system. They believe that the role of a heated boundary layer and larger-scale lifting ahead of the line make the successful simulation of this MCS quite unlikely using current nonhydrostatic modeling strategies that employ uniform conditions and do not represent the heated boundary layer.

James Fankhauser, Barnes, and Margaret LeMone have completed analysis of the 20 June 1981 squall line observed during the Cooperative Convective Precipitation Experiment (CCOPE). Data from five Doppler radars, the surface mesonet, aircraft, and rawinsondes were used to document the structure and evolution of the system. Unique features include strong tropospheric wind shear, low convective available potential energy, and relatively weak but unusually persistent rain cells.

The orientation of the squall line, composed of high-reflectivity cores spaced 20 to 40 km apart, initially was normal to the environmental shear vector, but over time moved into a parallel orientation as the northern portion of the line merged with convection ahead of the line. Consistent with prior numerical modeling results, the intensity of the cells within the squall line diminished as it became more parallel with the shear. Trajectory analyses based on the Doppler-derived wind field revealed that the primary source of air in the subcloud cold dome was boundary-layer air ahead of the line cooled by rain evaporation. There was no evidence of significant rear-to-front system-relative airflow in the subcloud air, which is typically observed beneath middle-latitude squall lines. Only a small fraction of the subcloud air originated at midcloud levels, probably because evaporation in air above cloud base was inhibited by high relative humidities in the environment and because comparatively weak updrafts produced only modest amounts of condensate for water loading. The behavior of this squall line is consistent with recent theories that characterize the structure according to the relative strengths of the horizontal vorticity in the low-level environmental wind shear and the vorticity generation at the leading edge of the subcloud cold pool. The squall line is representative of that part of the spectrum of mesoscale convective systems that does not have a rear inflow jet, does not produce a significant stratiform precipitation region, and does not rely upon penetrative downdrafts to sustain the air mass within the subcloud cold dome.

Mathematical Models of Organized Convection

The observed behavior of convective lines suggests that the simple picture of horizontal momentum transport by boundary-layer air from the front of the line to the rear as it ascends and by midlevel air moving from rear to front as it descends requires further refinement. To this end, Mitchell Moncrieff is developing a mathematical theory for quasi-two-dimensional mesoscale convective systems and their transports. This is an extension of his previous work that exploits the conservative properties of the nonlinear Boussinesq equations and represents the macroscale dynamics of MCSs in terms of five nondimensional numbers. These dimensionless parameters arise through the influence of three sets of processes: first, local baroclinic vorticity generation due to latent heating, evaporative cooling, and mean flow stratification (three convective Richardson numbers); second, the far-field, mean flow thermodynamic and velocity structure associated with gravity current dynamics (two Froude numbers); and third, the vertical integral of the pressure perturbation behind the system, normalized with respect to its propagation speed, that reflects the propagating hydraulic-like behavior. An archetype model defined by the theory is being used in the momentum transport parameterization and defines necessary conditions for conservative and nonconservative behavior.

Vertical Momentum Transport

LeMone, Fankhauser, and Thomas Matejka (National Severe Storms Laboratory, or NSSL) have completed preliminary analyses of momentum generation and redistribution within two squall lines in CCOPE, and are comparing them to convective lines in the tropics and subtropics. They hypothesize that differences in the budget can be explained to first order in terms of variation in mean environmental wind shear (normalized by the convective available potential energy). In the weak shear tropical cases the momentum and mass transports are consistent with air passing from the front to the rear of the system; boundary-layer air is accelerated from the front to rear (horizontal velocity, or u, < 0) by pressure forces as it rises (vertical velocity, or w, > 0) due to buoyancy, while middle-level air penetrates between towers, and feeds a downward-moving rear-to-front branch ($w < 0$; $u > 0$). Both of these contribute to momentum transports that are negative ($\overline{uw} < 0$) in the line coordinate system, with the largest absolute values at middle levels. Similar $\overline{uw}$ profiles arise in the moderate shear case, due to dominance of the upward-moving front-to-rear trajectory. However, overturning trajectories—air moving front-to-rear into the line, rising, and then reversing and exiting out the front side—cancel part of this effect at upper levels. In the strongest shear case, the overturning trajectories dominate. With front-to-rear rising flow at lower levels and rear-to-front flow at upper levels, $\overline{uw}$ is negative at lower levels but becomes positive at upper levels. Only in the moderate shear case is the u momentum transport downgradient (of opposite sign to the environmental shear dU/dz) at all levels. Qualitatively, the change in the u momentum flux behavior of the lines with increasing normalized shear is well-replicated by Moncrieff's mathematical theory.

A convective line in TAMEX, analyzed by David Jorgensen (NSSL) and LeMone, does not easily fit this pattern, showing positive values of $\overline{uw}$ in spite of small to moderate normalized shear. W.-K. Tao (NASA Goddard Space Flight Center) is simulating this line and collaborating with LeMone to understand the line's "anomalous" behavior.

Matejka and LeMone have also been examining the role of two-dimensionality on the generation and transport of momentum through analysis of the 17 July CCOPE squall line. A preliminary examination of the squall line reveals a cellular structure that becomes more two-dimensional as the system evolves from its mature to dissipating stages. Curiously, the momentum transport $\overline{uw}$ remains constant as the line's updrafts weaken and its general structure becomes more two-dimensional. This results from a rearward acceleration of u that is well correlated with the strong updrafts.

Multiscale Cloud Systems in the Tropical Western Pacific

Moncrieff, Terry Clark, and Wojciech Grabowski have begun a dynamical study of convective processes in the tropical western Pacific. The objectives include the organization of convection, its interaction with the boundary layer and surface processes, and its effect on the large-scale dynamics of the tropical atmosphere. Modeling and theory form the basis of the study with a view to providing hypotheses for testing in the Tropical Ocean and Global Atmosphere (TOGA) program's Coupled Ocean-Atmosphere Response Experiment (COARE).

Cold Air Outbreaks over the Sea of Japan

Masataka Murakami (visitor, Meteorological Research Institute, Ibaraki, Japan), Clark, and William Hall have been collaborating over the last year on simulating cold outbreaks over the Sea of Japan which lead to extensive snow storms in Japan. Using Clark's model with Murakami's ice physics, they have simulated two episodes in two dimensions and one in three spatial dimensions. The fields of clouds appear to be quite realistic compared with observations. The simulations indicate that the very active convection resulting from the cold outbreaks over the sea produces extremely strong exchanges of heat, moisture, and momentum. The pressure-gradient response reveals a cyclic nature to the mean/perturbation momentum exchange due to the convection. The results of this project are still under analysis.

Fronts and Squall Lines in TAMEX

Trier and Parsons have completed a collaborative study, with Matejka, of a subtropical cold front and associated convection observed during TAMEX on 8 June 1987. As this front moved into the TAMEX network, they showed that it was shallow (approximately 1–2 km in depth) but with marked baroclinicity (5–7° C temperature contrast) and an abrupt horizontal wind shift (approximately 1-km scale). They believe that these and other aspects of the observed front resemble the microscale structure of middle-latitude fronts. As the front moved through the TAMEX network, the thermal contrasts were weakened rapidly by fluxes from the warm subtropical ocean. This mechanism for the modification of surface fronts from strongly baroclinic systems to weak baroclinic Mei-Yu fronts had been previously proposed, but the analysis by Trier and his colleagues afforded the first documented example.

Parsons and Trier have also undertaken a study of prefrontal squall lines within this TAMEX system. These prefrontal convective systems accounted for heavy rainfall (in excess of 90 mm at some locations) over the southern portion of the island. Using proximity soundings to initialize a nonhydrostatic model, they have successfully simulated these prefrontal lines. The convective structure within the simulated systems contained intense, long-lived cells on the flanks of the line. Although the environment in the vicinity of the TAMEX system contained noticeably less convective available potential energy (~1000 vs. 2500 J/kg) than that found near long-lived (e.g., super-) cells in the midlatitudes, they found the bulk Richardson number for the TAMEX case is within the range where supercell occurrence is predicted by past observational and numerical studies.

Topographically Induced Circulations

Hawaiian Rainbands

LeMone and Jorgen Jensen (CSIRO/Mordialloc, Victoria, Australia) have completed an observational study of two types of rainband observed during the 1985 Hawaii Warm Rain Experiment—a stationary line of relatively isolated enhanced cloudiness, and a more continuous cloud line that is a miniature version of a tropical squall line observed over the equatorial eastern Atlantic in the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) and over the African continent in the French Convection Profonde Tropicale (COPT) experiment. Using pressure, wind, humidity, and temperature data from the University of Wyoming King Air, they determined the propagation speed of several clouds and constructed cross-sections of their perturbation pressure, wind, and thermal buoyancy [$(T_v - Tv_{ve})/\overline{T_v}$, where T_v is the virtual temperature, the overbar represents a leg average, and e denotes the environment]. The temperature in cloud is from the $L\alpha$ hygrometer and assumes saturation.

The stationary line of enhanced cloudiness that formed above the convergence zone upwind of the island was shown by Piotr Smolarkiewicz and Clark to originate from interaction of the island with the trade winds. The clouds moved downstream with the wind averaged through their depths, their buoyancy-induced low pressure drawing in air from the subcloud layer. After around 20 min (a typical time for tracking these clouds), the cloud would dissipate. Assuming that the convergence zone remains stationary over the lifetime of the cloud, a typical line-normal wind speed of 3–5 m/s, they estimate a range of bandwidths of 3.6 to 6 km. This is consistent with the width of the cloud bands from airborne videos (5–10 km) and estimates by Roy Rasmussen (3–7 km). This scenario is remarkably similar to that obtained by Rasmussen and Smolarkiewicz from analysis of numerical simulations.

Only one example of the squall-line-type band was observed. In this case, the line appeared to feed from the front, with warm moist air moving upward as it was accelerated rearward by a buoyancy-induced area of low pressure centered around cloud base. A comparatively large region of stratiform cloudiness lay to the rear of the active convection. All of these features are shared with the much deeper (12 km instead of 2–3 km) convective bands observed in COPT and GATE.

There is evidence that this line was propagating, another feature that it shares with the COPT and GATE lines: the maximum cloud lifetime of 2 h yields too large a cloud-line width when combined with the wind normal to the line; and the cross-sections generated here and by Takahashi both suggest a cold pool, which could help generate new convection ahead of the line.

Recent observations in HaRP suggest that Hawaiian rainbands are more commonly mechanically forced, with buoyancy playing a much more minor role than implied here. This apparent discrepancy probably results from the fact that the data set used here was collected to examine individual growing convective turrets, clearly associated with buoyancy, while the HaRP data were collected to assure a more global view of the rainbands.

Low-Froude-Number Flow Past Three-Dimensional Obstacles

In simulations of stratified flow past an axisymmetric three-dimensional hill, Smolarkiewicz and Rotunno found that lee vortices form when the Froude number is small. To account for the sense of vorticity within the lee vortices, they deduced the vortex-line pattern from steady inviscid linear theory and its next-order correction. They found that the vortex-line pattern computed from the fully nonlinear steady model solution is in excellent agreement with that expected from the theory. Since the publication of these results in 1989, several authors have suggested that the breaking of lee waves plays an important role in lee-vortex formation. One author conjectured that breaking lee waves may create potential vorticity in the lee eddies. His idea is that the creation of potential vorticity is *the* critical event since, in his view, a vortex in a stratified fluid is defined by its potential vorticity. Another set of authors argue that the wave-breaking process is important not so much because potential vorticity is produced, but rather because the tilting of horizontally oriented lines to the vertical is much stronger when there is wave breaking. Rotunno and Smolarkiewicz have conducted numerical experiments that provide evidence that lee vortices do not *require* potential vorticity and/or wave breaking for their formation. They have also found that the deductions about the sense of the vorticity in the lee eddies from the linear analysis of their 1989 results are robust in the sense that the same basic physical picture can be obtained even within a completely different analytical framework.

Terrain-Induced Vortices, Denver Cyclone

John Tuttle has analyzed several Convection Initiation and Downburst Experiment (CINDE) cases using Tracking Radar Echoes by Correlation (TREC) software to determine the structure and evolution of the mesoscale airflow in the boundary layer that promotes the initiation of convection. These studies are focused particularly on situations involving the Denver Cyclone, a zone of convergence and vorticity that often develops in the lee of the Palmer Divide south of Denver, under conditions of southerly to southeasterly ambient flow. The model results of Andrew Crook, Clark, and Moncrieff have shown that the nature of the cyclone is highly dependent upon the stratification and direction of the airflow. Two of the observed cases studied here, 28 June and 24 July, are quite consistent with this dependence.

On 28 June, the ambient flow was southerly and a well-defined mesocyclone 50–60 km in diameter was evident just east of Denver. The low-level flow was divergent (hence subsident) in the core of the cyclone and weakly convergent at the outer edges. Satellite images showed a cloud-free region collocated with the cyclone, also indicating subsidence. Over a period of several hours the cyclone drifted northward at about one-third the speed of the ambient flow and weakened considerably. The observations of the structure and drift of the cyclone are in good agreement with model results, although the model showed a somewhat faster drift. Interestingly, the period of decay was followed by rapid intensification as the airflow in the cyclone became convergent. Shortly thereafter a series of intense storms developed near the cyclone center and drifted eastward while the cyclone remained essentially stationary. Although the onset of deep convection was closely correlated to the intensification of the cyclone, the cause and effect is still a subject of investigation.

On 24 July the ambient flow was from the southeast, at an angle to the foothills. As the flow approached the foothills it turned counterclockwise, becoming northerly along the foothills. This resulted in a north-south convergence line stretching northward from the Palmer Divide about 70 km. By early afternoon a line of storms developed along the convergence zone. Model results for initial conditions similar to the observed environment indicated that the northerly flow develops because of Coriolis turning as the southeasterly flow approaches the mountain barrier and decelerates.

Crook, Clark, and Moncrieff have completed a numerical study of the boundary-layer circulations that develop downwind of a heated obstacle. This work is an extension of their earlier Denver Cyclone study which examined the adiabatic, low-Froude-number flow around an obstacle. When the obstacle is heated, significant horizontal shear develops in the lee as the flow converges at low levels and diverges above. Two types of instability then grow within this shear flow. At the lower levels of the boundary layer, convective rolls oriented along the shear vector are predominant, while a shearing instability aligned perpendicular to the shear vector appears higher in the boundary-layer These boundary layer circulations then force a gravity wave response in the overlying stratified atmosphere. The vertical velocity in these gravity waves exceeds 1 m/s in certain regions.

The interaction of these boundary-layer circulations with lee vortices such as the Denver Cyclone was also examined. Significant vertical vorticity develops at the points where the boundary-layer rolls intersect the lee vortex. These small-scale vortical circulations (which have been termed misocyclones) are often observed in conjunction with the Denver Cyclone and frequently produce small tornadoes in the Denver region.

Edward Szoke completed a case study of a Denver Cyclone that occurred during a day with an overcast of low clouds, providing observational evidence of the movement of the center of the vortex, which appeared as an "eye" of clearing. He found that the track of the visual center of the Denver Cyclone compared favorably to numerical modeling simulations by Crook, Clark, and Moncrieff for similar low-Froude-number conditions.

Szoke continued a collaborative study with John Augustine (NSSL), aimed at determining the significant kinematic and thermodynamic characteristics that separate Denver Cyclone days from other days, by compositing several years of mesonet and sounding data. Other stratifications of the data set addressed the characteristics important to the development of thunderstorms and tornadoes, contrasting days with and without a Denver Cyclone. The study not only provides an observational base with which to compare model results, but also useful reference material for operational forecasters. They found that in the mean there was a relationship between increased low-level stability and Denver Cyclone organization, in agreement with a number of modeling results. However, they found that the observed Froude number was not as low as that used for some experiments, suggesting that a number of other environmental conditions might support the development of a Denver Cyclone, and that therefore different causal mechanisms must exist. The tornado stratifications indicated that less vertical wind shear and instability exist in the mean on Denver Cyclone tornado days than on other tornado days, indicating the importance of the low-level forcing and local environment modification that promotes tornadogenesis under less-than-standard conditions.

Downslope Windstorms

John Brown, Robert Banta (both of NOAA), Clark, and Hall have been collaborating over the last year on a modeling/observational project aimed at predicting windstorms in the Front Range area. The focus of the project is to determine the utility of mesoscale models for predicting local windstorms as well as to further the understanding of their dynamics. Using data from a profiler located at Craig, Colorado, for initial conditions they simulated the 9 January 1989 Front Range windstorm. Initial evaluations of the model compare favorably with surface wind observations. The low horizontal resolution of 10 km used in the model gave a surprisingly high level of prediction. They found the structure of the windstorm to be both quite transient and three-dimensional in structure. High wind regions could be traced to the profile of the upstream orography and direction of flow. Regions of strong surface winds along the Front Range were also strongly correlated with regions of wave breaking aloft. This is an ongoing project that should help direct future observations both along and upstream of the Front Range.

Airflow and Cloud Pattern Simulations

Roelof Bruintjes (long-term visitor, South African Weather Bureau), Robert Gall (University of Arizona), Clark, and Hall are collaborating on a modeling study of airflow and modeling of clouds over the Mogollon Rim in North Central Arizona. This project is part of the Arizona Snowpack Augmentation Project funded through NOAA to the Arizona Department of Water Resources, and its overall purpose is to improve cloud seeding technology. Simulations have been carried out of a number of cases where tracers were released and followed by aircraft to determine the airflow characteristics. Comparisons between the model simulations and observations are indicating that the model is capable of realistically simulating the observed airflow patterns in three dimensions.

Gravity Wave Propagation

In certain situations, such as winds that increase rapidly with height, gravity waves may be trapped vertically, causing the wave energy to propagate horizontally downstream. Teddie Keller (visitor, IBM), Morton Wurtele, and Robert Sharman (both of the University of California, Los Angeles or UCLA) performed detailed comparisons of analytic solutions and numerical model results for both hydrostatic and nonhydrostatic gravity wave propagation in a sheared environment and investigated the effects of the stratospheric wind profiles on the leakage of energy through the tropopause. In some circumstances, the intrinsically nonhydrostatic waves could be partially trapped, affecting the vertical propagation of energy and momentum into the stratosphere. It was shown that these "leaky" modes are completely eliminated if the hydrostatic assumption is made *a priori*, demonstrating the importance of nonhydrostatic dynamics.

Thunderstorm Electrification

Microphysical and Electrification Measurements

Andrew Weinheimer (Atmospheric Chemistry Division, or ACD), James Dye, and Daniel Breed, in collaboration with Thomas Marshall (University of Mississippi), have analyzed microphysical observations made by the NCAR sailplane in a New Mexico thunderstorm using an induction cylinder in conjunction with a two-dimensional optical array probe (charge/image probe). The measurements are unique in that size, shape, and charge of hydrometeors were obtained simultaneously in the temperature range of −5 to −35°C, which is a critical temperature range in which electrification through noninductive charging by collisions of graupel with smaller ice particles may be important.

The observations show that the particles with detectable charges were primarily graupel particles, and the magnitude of the charges was consistent in general with laboratory measurements of ice–ice collisional charging. The fraction with detectable charge increases with size as does the magnitude of the mean charge. Also, the positively charged particles occur only at warmer temperatures, and the degree of negative charging increases with decreasing temperatures, which is consistent with laboratory findings of a sign reversal temperature for graupel charging.

However, one aspect of the results appears to be inconsistent with the noninductive collisional charging mechanism. Only 38% of the particles larger than 3 mm are charged to the level of detection, rather than 100% as would be expected. Possible explanations, within the context of this mechanism, rely on small-scale variations in microphysical structure and/or unknown time scales for particles to come into equilibrium with their microphysical environment. The researchers plan to address these topics with more extensive observations using the charge/image probe in future sailplane flights.

Sailplane Instrumentation

As a result of the analysis of this 1987 case study and further test flights in 1988 and 1989, the charge/image probe is being modified for improved operation in thunderstorm conditions. Improvements in the design will allow for more effective deicing of the probe, and it is hoped that a change in manufacturing and testing of the induction ring will eliminate some sporadic noise that may be due to wetting effects. Software changes in the probe's data handling system have also been identified that will lead to better determination of particle concentrations.

Analysis of the electric field measurements on the sailplane have led to a better understanding of the quality and limitations of those observations. The primary instrument for measuring electric fields (E-fields) has been a nose-mounted field mill (really four mills in one), built by William Winn and J.J. Jones (both from New Mexico Institute for Mining and Technology), which has demonstrated a noisy character in strong E-fields. The polarizing effect on the sailplane as it circles in an E-field periodically accentuates the aircraft charge on the nose and tail. If that induced charge is large, the E-field measurement, which is a result of the difference between two large numbers, can be affected by the amplification of small perturbations or errors that are dependent on calibration procedures, instrument design, or airframe asymmetries. The addition of two fuselage-mounted grounded-shutter type E-field mills in 1989 provided a redundant measurement at a more electrically neutral location and allowed for the determination of the third component of the vector E-field. The results of the 1989 flights allowed Weinheimer, Dye, and colleagues to refine the calibration of the nose mill and suggested an improvement in the electronic design. The redundant measurements also verified their suspicions that noisy periods during strong E-fields are probably due to coronal emission of ions when the fuselage is polarized the most (aligned parallel with the field lines as it circles). Identification of this condition is important for assessing the quality of the measurements in strong fields.

Under the direction of Breed and NCAR Research Aviation Facility personnel, the sailplane is undergoing an upgrade in the power distribution system and wiring, and an improvement in its data logging capabilities. The computer-controlled data recording design is the first phase of an overhaul of the entire data handling system. The instrumentation improvements, wiring upgrade, and data recording changes will be flight-tested in the spring of 1991 in preparation for a major field study in the summer of 1991.

Thunderstorm Electrification Modeling

Dye has been working with Conrad Ziegler, Don MacGorman (both of NSSL), and Peter Ray (Florida State University) on the modeling of the 31 July 1984 New Mexico thunderstorm. Extensive observations made in this storm by the sailplane showed that the electric field intensified exponentially from fair weather fields to fields sufficiently strong to initiate lightning in the short period of about 5 min. From the electric field observations Breed and Dye were also able to deduce that the region of negative charge in this early stage of electrification was associated with the high-reflectivity region at about $-15^{c}irc$ C. The model uses Ziegler's thermodynamic-microphysical retrieval techniques, the evolving Doppler-derived three-dimensional wind field, and the Keith and Saunders laboratory results on charge separation for graupel–ice particle collisions to see whether the noninductive ice collisional theory of charge separation can explain the rapid rate and observed electric field structure of this storm. Vertical velocity, liquid water content, and ice particle measurements from the sailplane were used to test and adjust the model output for these parameters.

Comparison of model output with the in situ observations reveals that the early electrification rate and the electric field distribution are consistent with the action of the noninductive mechanism in concert with the evolving convective motion. Increases in ice particle concentrations and sizes, spread of the volume containing significant ice concentrations, graupel sedimentation in the updraft, and vertical flux convergence of the updraft in the region of about -5 to $-25^{c}irc$C all appear to contribute to the rapid, exponential growth of the electric field. When inductive, i.e., electric field–dependent, charging for droplet-graupel collisions and rebound was included, maximum electric fields in the model decreased.

The combined observational-modeling work is an important step in demonstrating the potential importance of the noninductive graupel-ice collision theory. The inductive theory has had considerable appeal for many years because in the inductive theory the amount of charge that can be theoretically separated is dependent on the strength of the electric field and thus could naturally lead to the observed exponential increase of electric field. The in situ observations from the sailplane in concert with the modeled and Doppler-derived wind fields now suggest that the evolving nature of the precipitation and air motion fields in combination with noninductive charge separation are more likely responsible for the exponential growth and early electrification of this thunderstorm.

Convection Initiation, Entrainment, Cumulus Interactions with Gravity Waves

Convergence-Line Tornadoes

A case exhibiting misocyclone-spawned tornadoes occurred on 17 July during CINDE. G. Brant Foote, James Wilson (Atmospheric Technology Division, or ATD), Fankhauser, Charles Wade, and Tuttle have analyzed the observations of several misocyclones along the Denver Convergence Zone and compared them with numerical simulations by Crook, Clark, and Moncrieff discussed above. As in the numerical simulations, the misocyclones tend to form at the points where boundary-layer rolls intersect with the Denver Cyclone. Analysis of the numerical results indicates that the vertical vorticity is primarily due to the stretching of ambient vorticity along the convergence line.

Cumulus Entrainment

Grabowski and Clark continued to study the dynamics of the cloud-environment interface where environmental air is entrained into convective clouds. They derived a theory that describes the temporal evolution of the laminar shear layer at the edge of a rising two-dimensional thermal. This theory indicates that the shearing velocity (the shear layer thickness times the vorticity) is independent of the eddy mixing because the layer thickness and vorticity magnitude are respectively proportional and inversely proportional to the square root of the eddy mixing coefficient. As the shear layer evolves, instabilities produce entraining eddies. In twin experiments, the time and spatial scales of these eddies were isolated. The energetics of the eddies were also analyzed to clarify the nature of the instabilities. Grabowski and Clark are continuing this research with two-dimensional experiments that include environmental shear and with three-dimensional experiments of rising thermals.

Interaction between Gravity Waves and Convection

Three-dimensional simulations of the Hawaiian rainbands have shown that the convergence line associated with the development of the cloud bands launches gravity waves. To understand the dynamic importance of these waves with respect to the bands, Teddie Keller and Moncrieff have investigated the interaction between the gravity waves and convection. Two-dimensional simulations show that gravity waves develop and are sustained for many hours in this rainband environment. Comparisons between dry and moist simulations reveal that the development of moist convection does not alter the wave pattern significantly. In the moist runs, convective cells develop continually and move into the wave pattern. Thus, the wave perturbations create an environment favorable for long-lived convection, even though the mean flow has little or no shear.

Cloud and Precipitation Physics

Hydrometeor Evolution

L. Jay Miller and Foote are investigating the role of water-drop shedding by existing hail in the continued production of hail in a Montana severe storm (the 1 August CCOPE storm). In their study of this storm, Rasmussen and Andrew Heymsfield had concluded that water-drop shedding likely played a significant role in the steady-state production of hail. Three types of shedding behavior are identified: (1) shedding from wet growth where hailstones are collecting cloud water faster than it can be frozen; (2) shedding from melting hail where the air surrounding the hailstone is warmer than 0°C but contains no cloud water; and (3) shedding from warm accretion where the surrounding air is warmer than 0°C and cloud water is present. Hailstones undergoing type (1) or (3) shedding are located within updraft, the only place where cloud water is assumed to exist.

In an earlier study of this storm Miller, Tuttle, and Foote found that the primary embryo source for the initial cycle of hail was most likely small cloud towers upwind of the main updraft. Embryos from any other locations in the storm were incapable of producing significant hailfall. Initial hail growth from embryos that originated in flanking cloud towers was followed by two progeny cycles, with each growth cycle taking about 15–20 min. Some embryos for these progeny cycles came from water drops shed by hail that was growing wet in the 5–8 km layer, but most came from hail that was either melting or accreting in the warm layer (3 to 5 km) of the storm. Further, the area of precipitation produced by growth from these secondary embryos alone narrowed with time, migrated downwind away from the diagnosed embryo source regions, and finally disappeared.

It is clear from these results that water-drop shedding from existing hail could not sustain hailfall for more than about 30–40 min, and that a source of primary embryos was needed since the storm produced hail for more than 90 min. Further, the largest hail diameters predicted by growth from shed drops decreased from 5 to 2 cm, while sizes estimated from radar measurements exceeded about 3 cm throughout the period. The amount of water shed in each event, a measure of the possible number of stones produced, was found to be only modestly sensitive to the formulation of fractional portions of water and ice of hailstones in the microphysical model, which was based on laboratory measurements. Shedding apparently acted to multiply and prolong for a short time the hail process in the studied storm; however, it could not explain the sizes and much longer duration of hail that was observed.

First Echo Studies and Precipitation Formation

It is difficult to understand how very new clouds can develop significant radar echos so quickly based on our current understanding of how droplets form and grow. Charles Knight has been studying this process in both the North Dakota Thunderstorm Project (NDTP) and HaRP through coordinated radar scans of small nearby cumulus and visual time-lapse photography. The continental cumulus in North Dakota exhibited a visibility threshold on radar at about −20 to −15 dB reflectivity (Z_e) as soon as cloud was visible to the eye, and characteristically the very small cumuli provided a weak echo from their sides and top: inverted cup-IBM) cup-shaped echoes. The source of this echo has not yet been definitely established. The HaRP data reveal stronger radar echos from similar-sized clouds as they first become visible optically. Indeed, in Hawaii it is fairly common for the radar echos to precede visibility, and the small clouds tend to provide radar echos throughout, not just along the top and sides. The first echo HaRP observations include a small amount of coordinated aircraft data that should help determine whether the echo comes from turbulent fluctuations in the index of refraction or from hydrometeors. The initial evidence seems to favor hydrometeors (still very tentative), which must apparently originate from giant salt (haze) particles.

Knight also found, in HaRP, vigorous, small, isolated cumulus clouds with precipitation shafts of 40–50 dBZ_e extending to the ground, but no *visible* sign of precipitation. This implies that the precipitation is composed of several-millimeter diameter drops at concentrations of 1–10/m, but unexpectedly few smaller raindrops. The big drops are too sparse to produce smaller ones by collisional breakup, and may themselves arise from small concentrations of giant nuclei.

Polar Stratospheric Clouds

Dye, Darrel Baumgardner (ATD) and Bruce Gandrud (ACD) have continued the analysis of particle measurements obtained by the Particle Measuring Systems forward scattering spectrometer probe (FSSP), Model 300, during the Airborne Arctic Stratospheric Experiment which was conducted from Stavanger, Norway during early 1989. Examination of the particle size distributions shows a consistent picture for the polar stratospheric clouds (PSCs) sampled by the NASA ER-2 aircraft during this mission. The type I PSCs, i.e., those thought to be formed by the cocondensation of nitric acid and water as nitric acid trihydrate (NAT), had modal sizes of about 0.6 to 1.0 μm and concentrations of 5–15/cm^3. These sizes are consistent with previous measurements by extinction from satellites and airborne lidar but provide considerably more detail of the particle size distribution. The concentration measurements suggest that the background sulfuric acid droplets do indeed act as the primary nuclei for the type I particles, although at times the FSSP 300 measured higher concentrations than those expected for the sulfuric acid droplets. Thus, there remains some question about other nucleation sources or uncertainties in measurement.

On a few occasions larger particles (> 4 μm) were also observed. However, these were only observed when the ER-2 was flying near water saturation or when water saturation existed 1 or 2 km above the ER-2 and could have fallen to the ER-2 level. Thus, it seems likely that these larger particles are the type II, ice-like, particles inferred from satellite and lidar measurements. Particles as large as 20 μm, the largest size threshold of the FSSP 300, were observed on a couple of days. For the 30 January 1989 flight Gandrud showed that the observed volume was considerably larger than that of the available nitric acid, which also suggests that the particles were predominantly ice.

Surprisingly, the measurements of type I particles showed that the temperature at which the ER-2 had entered the main body of the PSCs was relatively uniform at about 191 to 193 K. If cooling rate is a dominant factor in determining the number of type I particles nucleated from presumably frozen sulfuric acid droplets, as has been assumed previously, one would not expect a striking dependence upon temperature. This finding led Dye to suggest that perhaps only some of the sulfuric acid droplets are frozen at 196 K when NAT could first start to form, and that the remaining sulfuric acid droplets freeze homogeneously at slightly colder temperatures. A temperature of homogeneous freezing at about 192 to 193 K is consistent with the phase diagram for hydrates of sulfuric acid and water, and large supercoolings of bulk sulfuric acid solutions have been reported in the literature. This might account for the rapid appearance of the type I particles near this temperature. Analysis of the particle measurements is continuing in conjunction with the measurements from other investigators to address this and other questions of nucleation of the particles and also the chemical composition of the particles.

Cloud Condensation Nuclei

Jan Rosinski, unaffiliated visitor, has obtained evidence that the evaporation of cloud droplets produces very active ice nuclei. He used filter samples to determine that such particles could be very active either as condensation-freezing or sorption nuclei, and their activity apparently was enhanced by the presence of the $SO_4^=$ ion. The measured concentrations of ice nuclei were very high in comparison to conventional measurements, and Rosinski speculated that these observations might explain the high ice concentrations reported, in e.g., maritime clouds of Australia, evaporating regions of clouds in the Pacific Northwest, or thunderstorm outflows.

Wave-Cloud Studies

Heymsfield and William A. Cooper conducted flight programs to observe the microphysical characteristics of wave clouds to investigate the formation of ice in these clouds and, in conjunction with Don Hagen (University of Missouri), the associated cloud condensation nucleus distribution. The analysis approach uses the aircraft microphysical, temperature, and vertical velocity measurements in combination with a detailed water droplet and ice particle growth model being run by Larry Miloshevich to determine the rates of homogeneous and heterogeneous nucleation as a function of temperature. Early results have documented a rapid homogeneous nucleation process occurring at about $-37^{c}irc$C, approximately as expected from laboratory experiments, and surprisingly low concentrations of heterogeneously formed ice particles even near the homogeneous nucleation threshold. The patterns of ice formation indicate a rapid onset of nucleation in both homogeneous and heterogeneous cases and a correspondingly rapid decrease in the ambient relative humidity.

These wave clouds provide a test bed for two newly developed instruments which it is hoped will provide critical new information: a low temperature (cryogenic) hygrometer (developed by ATD) and a continuous "small" ice particle sampler. Relative humidity is fairly well known at times when liquid water is measured by a variety of sensors; similarly, ice saturation is known when high ice concentrations are detected from two-dimensional imaging probes. This information will be helpful in estimating the accuracy and time response of the cryogenic hygrometer. Wave clouds are thought to contain small hydrometeors and thus can be used to evaluate the performance of the small ice particle detector.

Altocumulus and Cirrus Clouds

Heymsfield, Miloshevich, and Anthony Slingo (Climate and Global Dynamics Division, or CGD) studied the microphysical and radiative processes active in altocumulus clouds sampled with the NCAR King Air during FIRE in 1986. This study involved an analysis of data from two altocumulus clouds and comparison with numerical modeling studies. They found that calculations of droplet concentration and mean diameter as a function of height above cloud base compared favorably with the measurements when entrainment effects were considered. They also found from radiative transfer calculations that radiation played an important role in driving convection in the more dynamically unstable of the two clouds.

Heymsfield and Thomas Ackerman (Pennsylvania State University) organized a special issue of *Monthly Weather Review* encompassing the results of an investigation of the microphysical and radiative properties of a cirrus cloud sampled during FIRE. The main finding of these studies was that particle sizes inferred from satellite data were appreciably smaller than those measured with aircraft, although the aircraft instruments could not detect ice particles below about 25 μm. This result implies that there is an abundance of unmeasurably small ice crystals and/or that the optical properties of ice crystals as detected by satellite radiometers are being modeled improperly. The finding has prompted the development of new aircraft instrumentation to understand the reason for this discrepancy, the so-called small particle anomaly.

Fundamental Physics of Ice Formation

Knight has continued efforts to isolate and identify a new antifreeze material from yeast, and to characterize and understand the antifreeze behavior of certain artificial polypeptides and other organic polymers. He found that these materials do exhibit antifreeze behavior; however, the problem of translating these findings into useful knowledge or products is proving difficult.

Marine Stratiform Clouds

Marine stratocumuli are known to play an important role in the global radiation budget, but the processes that form and dissipate them are presently not well understood. Chin-Hoh Moeng, Donald Lenschow, and Ilga Paluch, in collaboration with many university investigators, are studying this subject using large-eddy simulation (LES) techniques and observational data from the FIRE stratocumulus experiment.

Composite Structure

In order to see to what extent our knowledge of the clear convective planetary boundary layer (PBL) can be applied to the stratus-topped PBL, Moeng and Ulrich Schumann (German Institute for Atmospheric Physics, Oberpfaffenhofen) conducted comparative simulations of an idealized stratus-topped PBL where the turbulence is maintained solely by cloud-top radiative cooling, and a clear convective PBL where the turbulence is maintained solely by surface heating. They applied a conditional sampling technique to both simulated flow fields to delineate structures of typical updrafts and downdrafts, and found that the updrafts within the cloud-top cooled PBL are nearly as strong as the downdrafts that are directly driven by the cooling. This is contrary to results for the bottom-heated PBL, where the downdrafts are much weaker than the updrafts that are directly driven by the heating. Their explanation is that in the top-cooled PBL, the coldest air parcels exist at the top of updrafts. These cold parcels partially mix with the entrained warm air before they are forced (by flow convergence) downward; only after descending from the cloud top are they driven by buoyancy. On the other hand, in the bottom-heated PBL, the warmest air parcels form updrafts that are buoyantly driven near the surface as well as throughout most of the PBL. This behavior has important implications for the entrainment and kinetic energy generation processes in the cloud-capped PBL.

Plume Fluxes and Budgets

Schumann and Moeng also studied quantitatively the fluxes and budgets of "plumes" using several indicator variables (vertical velocity, moisture, and the combination of the two fields) to define the plume. The LES results agree in general with existing observational studies. Schumann and Moeng found that the plume fluxes are best characterized in terms of vertical velocity. They also obtained LES formulations for the mass-flux coefficients that are needed in various mass-flux PBL models.

Sensitivity of LES Stratus Dynamics to Cloud Microphysics

Moeng and Judith Curry (Pennsylvania State University) implemented a simple cloud microphysics scheme into Moeng's LES code that takes into account some effects of drop-size distribution in calculating the gravitational settling flux and long-wave radiative cooling rate, as a first step toward determining the importance of cloud microphysics in stratus cloud dynamics. They found that including the gravitational settling effect changed only the liquid water flux, while other turbulence statistics remain nearly the same. They argue that the strong turbulent mixing within the simulated field always maintains a linear profile for the total moisture flux, and the addition of the gravitational flux changes the liquid water flux in such a way that the total moisture flux remains unchanged. The change in the liquid water flux apparently is not large enough to modify the buoyancy flux profile and therefore the turbulence dynamics.

Stratus-Topped PBL Simulations

Moeng continues to collaborate with David Randall and Qingqiu Shao (both of Colorado State University) in developing a simplified PBL model that allows for partial mixing and partial cloudiness within the PBL for global circulation models. The closure parameters involved in the model will be determined from Moeng's LES results.

Paluch and Lenschow have analyzed observations of marine stratocumuli in a region several hundred kilometers west of the southern California coast, collected FIRE. During this field experiment single, uniform stratus layers were rarely encountered. Typically the observed stratus layers were broken and patchy, and on most research days there were cumuli, patches of fog, or secondary cloud layers below the upper stratus deck. Based on their observational studies, Paluch and Lenschow suggest the following life cycle of a marine stratus layer as it forms when the sea surface temperature is warmer than the air above it: In absence of cloud cover, the inversion is typically not sharply defined, and there is a transition layer where both potential temperature and moisture change rather gradually with height. Condensation starts in this transition layer where the temperature is stably stratified and moisture is transported through small-scale turbulent eddies. The newly formed cloud layer can be expected to have a rather uniform appearance, with only local fine-scale nonuniformities reflecting the small eddy scale. If there are gravity waves near the inversion, then the first clouds may form as thin layers at the wave crests (Fig. 1). As the cloud layer grows, its top is cooled by radiation and the inversion becomes sharply defined. Because the cloud is now colder than the adjacent clear air, baroclinic circulations develop, producing patchy cloud structure near the cloud layer boundaries. Intermittent entrainment at the cloud top and variations in the sea surface moisture fluxes may create additional horizontal nonuniformities in the cloud layer (Fig. 1b). If the cloud layer reaches the precipitation stage, evaporation of precipitation moistens and cools the air below (Fig. 1c). The temperature and moisture profiles will tend to approach the wet adiabat. Since the temperature profile is now stable with respect to dry ascent, more heat and moisture can build up near the surface. Eventually, this may lead to convective instability, causing cumuli to form below the stratus deck (Fig. 1d). In time the stratus deck may disintegrate because of mixing at

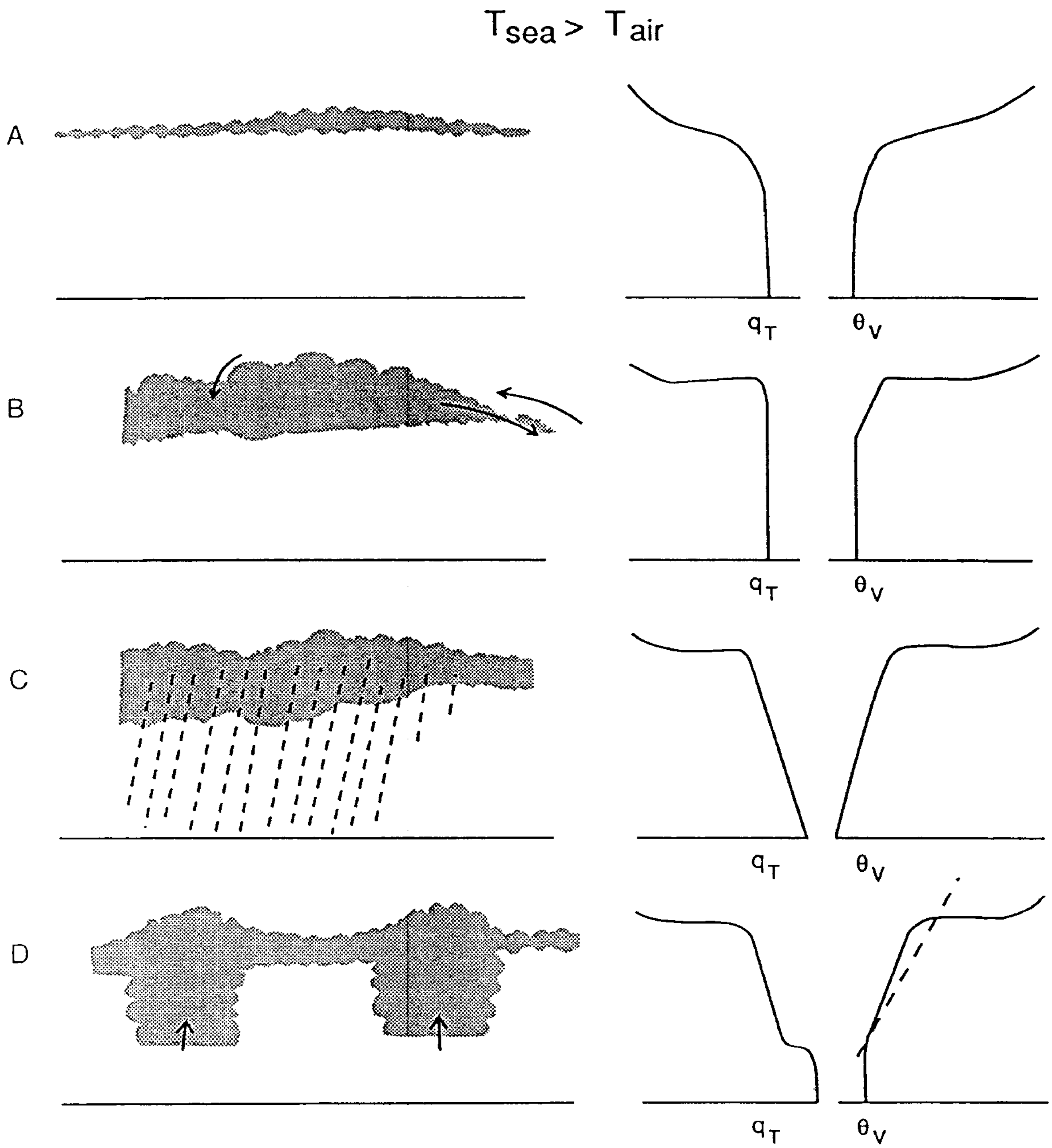

Figure 1. Life cycle of a marine stratus layer as it forms in the presence of surface heating with corresponding profiles of total water (q_t and virtual potential temperature (θ_v). The dashed line in D represents the wet adiabat.

the top, leaving a field of cumuli behind. Finally, if the moisture supply persists, the cumuli may grow in numbers and merge to form a new inhomogeneous cloud layer. This investigation suggests that the single, uniform stratus layer can only exist in restricted circumstances, and may explain why such layers are relatively rare compared to other, more complex cloud forms in the marine boundary layer.

Boundary Layers and Turbulence, and Chemical Transport

Large-Eddy Simulation

John Wyngaard and Moeng studied the different diffusion properties of scalars whose source is at the top of the PBL (top-down diffusion) or at the bottom (bottom-up diffusion) through the joint probability density (JPD) of vertical velocity and scalar concentration. They derived these JPDs through large-eddy simulation of a convective PBL. They showed that the two JPDs are strikingly different, even though both exist within the same turbulent flow field. Updrafts carry more scalar flux than downdrafts; throughout most of the mid-PBL, updrafts are responsible for about 70% of the flux in the bottom-up case, and about 62% in the top-down case. The mass-flux coefficient in the "relaxed eddy accumulation" technique proposed by Joost Businger and Steven Oncley (ATD) is about 0.6 for bottom-up diffusion and about 0.47 for top-down diffusion. For a jointly Gaussian JPD, Wyngaard and Moeng obtained an analytical value for the mass-flux coefficient of 0.627, which is close to that of the bottom-up scalar. This is consistent with their finding that bottom-up diffusion is closer to joint Gaussian than is top-down diffusion.

Moeng, Wyngaard, James McWilliams, Joseph Tribbia (both of CGD), Albertus Holtslag (long-term visitor, Royal Netherlands Meteorological Institute, De Bilt), and Anders Andrén (visitor, Uppsala University, Sweden) continued their assessment and development of PBL models used in large-scale numerical models of the climate system. They plan to assess how current PBL models perform against experimental data bases and against LES results, and to design models that have the improved physics and performance required in the future. So far, they have reviewed current PBL models and designed a few representative one-dimensional models for evaluation. This project is being carried out under the sanction of the World Climate Research Program.

Moeng also worked with Holtslag on developing expressions for eddy diffusivity and countergradient transport in the convective boundary layer. They showed that the well-known countergradient effect is due to the turbulent transport, not to buoyancy as suggested by James Deardorff. Holtslag and Moeng's formulation also takes into account the different diffusion properties of top-down and bottom-up processes.

Stochastic Particle Modeling

Jeff Weil (long-term visitor, University of Colorado) is using Lagrangian stochastic models to compute scalar dispersion in the convective boundary layer (CBL), forest canopies, and clouds. The model is a statistical approach in which random "particle" trajectories are followed in a turbulent flow where the Eulerian velocity statistics are specified.

For the CBL, he analyzed the asymmetric transport properties of bottom-up and top-down diffusion. Weil showed that the main cause of the asymmetry was the skewness (S) of the vertical velocity (w) with an additional contribution arising from the vertical inhomogeneity of the turbulence. The skewness effect was explained in terms of the particle kinematics: At the boundaries, particles are constrained to move away from the source with positive velocities in bottom-up diffusion and with negative velocities in the top-down case. For $S > 0$, the probability density function (PDF) of w is biased toward larger positive and smaller negative values than in Gaussian turbulence ($S = 0$). Thus, in skewed turbulence, particles originating from a surface source are transported upwards more rapidly than in Gaussian turbulence, and the converse is true for a source at the top.

These results and the earlier ones from LES led Wyngaard and Weil to a simple theoretical analysis of transport asymmetry in skewed turbulence. Using a kinematic dispersion model for homogeneous turbulence, they showed that the transport asymmetry results from the interaction between the vertical velocity skewness and the scalar flux gradient. The gradient arises from the scalar flux imposed at one boundary (bottom or top) with a zero flux at the opposite one. Their model, valid for small-time-scale turbulence, showed that the effective eddy diffusivity for bottom-up diffusion developed a singularity near the top of the CBL whereas for the top-down case it was positive and well-behaved; this was qualitatively similar to the LES and stochastic model results. Wyngaard's heuristic model of convective turbulence also suggested that the asymmetric transport was described by the kinematic model, but the small-time-scale restriction was removed.

In collaboration with Thomas Horst (ATD), Weil recently used the stochastic model to predict flux "footprints"—the horizontal distribution of the vertical turbulent scalar flux at a fixed height—from a continuous surface area source in the PBL. This has application to the determination of surface fluxes (e.g., of chemical species) from tower or aircraft measurements. Footprints from the stochastic model were computed for a source in the neutral surface layer and were in good agreement with a similarity model, which has been "field tested." Similar calculations are now being made for arbitrary heights in the CBL where the stochastic model is applicable but the similarity model is not. These results should be useful, for example, in deployment of the NCAR ASTER (atmosphere/surface turbulent exchange research) facility for experiments related to the Global Tropospheric Chemistry Program, such as the Atmosphere/Ecosystem Gas Interchange Study (AEGIS). Future modeling will address the inverse problem of computing the surface flux distribution given the footprint at some height above the surface.

On a related problem, Weil is modeling mean field dispersion—concentrations, vertical fluxes, and K (eddy diffusivity) profiles—within and above forest canopies. This is aimed at the development of simple parameterizations of scalar fluxes to and from the canopy that would ultimately be used in global climate models. For dispersion, the turbulence in canopies must be treated as two-dimensional (in the longitudinal and vertical directions), skewed in both components, and vertically inhomogeneous. These properties complicate the stochastic model, and only approximate modeling of the turbulence/dispersion is possible at present. Computations have been made for line, (horizontal) area, and volume sources of a scalar. Qualitative agreement has been achieved with wind tunnel data (line, area sources) and with field measurements in an Australian pine forest (volume source).

In collaboration with Paul Lawson (long-term visitor, SPEC, Inc.) and Alfred Rodi (University of Wyoming), Weil is using a two-particle stochastic model to calculate relative dispersion of ice in seeded cumulus clouds; such dispersion is about the moving center of gravity of the ice cloud and is necessary to compute the fluctuating concentration field. Although the model is restricted to homogeneous turbulence, it agreed well with relative dispersion measurements in High Plains Experiment (HIPLEX) cumuli. An important part of the analysis was the determination of appropriate averages of cloud turbulence—root-mean-square (rms) velocity and dissipation rate—and relative dispersion as a function of time. This was done by averaging these variables at fixed times after the ice cloud formation from all cloud realizations, i.e., measurements on different days but with broadly the same cloud characteristics. In addition to agreement with the observed mean relative dispersion, the modeled PDF of the two-particle separation was in agreement with the observed PDF of the relative dispersion at early times but was more peaked (i.e., narrower) later. They speculate that this is due to the finite dimension of the cumuli; in contrast, the model applies to an unbounded flow. This difference as well as the time decaying nature of the cloud will be addressed in future work.

Direct Numerical Simulation

It is known that spectral turbulence theory may be used to derive large-eddy simulation methods. However, recent direct numerical simulations carried out and analyzed by Robert Kerr and Jackson Herring have indicated that the statistical theory is not adequate to cope with some of the more subtle features, such as the correlation of vorticity and strain that tend to develop in inviscid flows. For finite viscosity, the situation may be somewhat improved, but the presence of coherent features in high-Reynolds-number flows suggests that the statistical theory must be improved and refined before it can cope adequately with such features. To study this problem, Herring and Kerr have undertaken a series of high resolution (256^3) numerical simulations for both zero and small viscosity. A key problem here is to understand to what extent these structures penetrate the inertial range. Their findings suggest that large fluctuations in the pressure variance are a good diagnostic of structures. Since this quantity is an ingredient of the statistical theory, it may be possible to propose a simple modification that will improve agreement between direct numerical simulation (DNS) and theory. Initial analysis suggests that the singular, power-law behavior and alignment of strain found in the idealized case is generally applicable. In most of the viscous calculations two passive scalars were used to determine the properties of scalar advection and potential vorticity. In addition, Charles Hesselbrink (University of Houston) will be doing visualizations, and Robert Kraichnan and Yoshifuma Kimura (both at Los Alamos National Laboratory) will be analyzing spectra and distribution functions from the 256^3 data sets. A goal of this work is to incorporate the effects of structures (including near-boundary effects) in statistical theories, such as large-eddy simulations.

Potential vorticity (PV) plays an important role in theoretical studies of large-scale motions in the atmosphere and oceans. Central to this point is Ertel's theorem, a statement that PV is conserved along particle trajectories. Herring, Kerr, and Rotunno have recently investigated the behavior of Ertel's PV in direct simulations of decaying turbulence. They showed that although PV is advected like a passive scalar, its dissipation occurs over a wide range of scales, and is not concentrated in the velocity or scalar dissipation regimes. Thus, attempts to use potential vorticity as a scalar marker are flawed. Their calculations suggest a simple scaling of PV dissipation which implies that for isotropic turbulence PV decays roughly exponentially on a time scale $\sim (L/u_{rms})R_\lambda^{1/2}$, L being the integral scale, u_{rms} the large-scale rms velocity, and R_λ the microscale Reynolds number. The calculations also suggested that the variance of PV is far from Gaussian, even at modest R_λ.

Perhaps the simplest measurement of turbulence is a single-point time record of a velocity component or scalar field, such as temperature. Yet the triple-point correlations of such records, the *bispectra*, contain essential transfer information. Herring and Olivier Métais (University of Grenoble, France) have made detailed comparisons of bispectra (for velocity and temperature fields) from theory and numerical simulations for low-Reynolds-number flow. Bispectra are a generalization of cospectra, a frequently measured aspect of atmospheric turbulence. The results indicate that for large and order unity Prandtl numbers, the statistical theory gives valid insights into the bispectra. The goal is to use bispectra as a tool to diagnose the type of turbulence (i.e., the degree of stratification, and the associated presence of waves and convection). In the limited study so far, they have found that bispectra are a sensitive guide to the qualitative features of turbulence—such as whether the field under study is a scalar or velocity field.

The acquisition of the CRAY Y-MP and the conversion to the UNICOS operating system have facilitated Kerr's model calculations of both inviscid antiparallel vortex reconnection and convection in a channel with his community turbulence model. The purpose of the reconnection calculations was to search for a singularity of the three-dimensional incompressible Euler equations. By using symmetries and mesh refinement, the calculation achieved the same resolution as a 1024^3 periodic box with uniform mesh spacing. These calculations show power-law behavior consistent with a singularity, and a new type of vorticity structure near the singular point. The new vorticity structure appears to be related to a particular alignment of the rates of strain with the vorticity that was previously observed by Kerr.

The purpose of the convection calculations was to investigate a new turbulence regime, called "hard turbulence," recently discovered at the University of Chicago, that does not obey classical scaling relations. Preliminary calculations done by Wanshu Wu (ASP graduate research assistant) and Kerr suggested the feasibility of reaching the hard turbulence regime. With the availability of the Y-MP, it was possible to reach Rayleigh numbers sufficiently high to have a distinct turbulent inertial subrange. From these calculations it appears that the transition to hard turbulence is associated with a transition to fully developed turbulence, with the classical scaling relations only applying to the low-Rayleigh-number quasi-laminar regime. Velocity statistics in hard turbulence are consistent with those in isotropic turbulence, even though it exhibits an anomalous temperature spectrum that is consistent with the experiments. It has also been determined that there is a strong aspect-ratio dependence in the simulations, a result that has since been confirmed experimentally.

Kerr and Wu also used the turbulence model to simulate convection in a sheared environment, with an emphasis on understanding the role of helicity in tornadic thunderstorms. While the simulation results do not support a direct role of helicity in the formation of tornadoes, as suggested by Douglas Lilly (visitor, University of Oklahoma), they do show a substantial reduction in the production of turbulent kinetic energy for strongly helical flows. This effect could promote the energetics directly responsible for the formation of tornadoes, thereby supporting the claim that helicity might serve as a predictive tool for the appearance of tornadic storms.

Kerr continues to collaborate with Davinder Virk (ASP graduate research assistant) and Fazle Hussain (University of Houston) on compressible reconnection. Virk has shown that the type of initial conditions used in most calculations of compressible turbulence leads to spurious "shocklets" that can be suppressed by making the initial density depend on pressure in the way predicted by the equation of state. The objective is to initialize on a slow manifold which suppresses shocklets and acoustic waves. He is now beginning some calculations of compressible turbulence with these initial conditions.

Model Development and Data Assimilation

Assimilation and Retrieval of Moisture Information

Although there has been significant progress in the development of remote sensing instruments (such as the Doppler radar wind profiler and the radioacoustic sounding system), our ability to measure water vapor remotely is still rather limited. Even the most advanced systems, such as the high-resolution interferometer sounder (HIS), yield watervapor observations having a vertical resolution of approximately 200 mb. However, most of the instruments can measure the vertically integrated quantities such as the precipitable water with a high degree of accuracy. The challenge of mesoscale data assimilation is to make the best use of these remote sensing measurements in developing algorithms to recover the vertical structure of the water vapor distribution, and initialize mesoscale models. Kuo and Yong-Run Guo (a long-term visitor from Shanghai Meteorological Center, PRC) have developed a method to assimilate precipitable water measurements (which could be provided by a ground-based microwave radiometer or HIS) into the MM4 model. They tested the algorithm using 3-h special soundings available from the Severe Environmental Storms and Mesoscale Experiment (SESAME) 1979 experiment. The results showed that the assimilation of precipitable water improved the precipitation forecast of the model. In return, the model provided a much better estimate of the vertical structure of water vapor than statistical methods based on climatology.

Advanced Mesoscale Data Assimilation and Forecast System

MMM and the NOAA FSL are collaborating to develop an advanced mesoscale data assimilation and forecast system. Philip Haagenson and David Gill, together with Stanley Benjamin and Patricia Miller (both of FSL), have developed a preliminary version of a modeling system that integrates components of the MM4 model with the Mesoscale Analysis and Prediction System (MAPS) of FSL. The MM4/MAPS system enables model initialization either with the MAPS hybrid (σ-θ vertical coordinate using optimal interpolation for the objective analysis) or with a Cressman objective analysis on pressure levels. They have conducted tests on several cases to demonstrate the feasibility of near real-time forecasts with the availability of a real-time data stream from FSL. A high-resolution version of the

MM4/MAPS model (90-km coarse grid, 30-km finer grid, and 23 vertical levels) will be used to provide real-time forecasts for the operations of the WISP during January-March 1991.

Nonhydrostatic Mesoscale Model

Jimy Dudhia (long-term visitor, Pennsylvania State University) has developed a nonhydrostatic version of the MM4. A transformed reference pressure as a vertical coordinate is used to minimize the changes required to the physical parameterization routines used by MM4. Computational efficiency is achieved using a separate small time step to stabilize the acoustic modes. He has completed the development of both a two-dimensional version and a three-dimensional version of the nonhydrostatic model. Tests with the two-dimensional model verify its ability to handle cloud microphysics and moist thermals on grid scales down to 1 km. Dry flow over a bell-shaped hill of half-widths from 50 m to 50 km demonstrated the model's ability to simulate both nonhydrostatic and hydrostatic lee waves that are in agreement theoretical results. Intercomparisons between the hydrostatic and nonhydrostatic three-dimensional models on a 20-km resolution with full physics have been initiated. Two cases chosen include a TAMEX mesoscale vortex case, where the steep terrain of Taiwan provides a test for the model, and an East Coast cyclogenesis case, where frontal structure and rapid pressure falls are of interest. Preliminary results show reasonable agreement on this essentially hydrostatic scale.

Limited-Area Spectral Model

Qiu-Shi Chen (long-term visitor, Beijing University) has been working with Kuo to develop a hydrostatic limited-area spectral model based on a harmonic-sine series expansion. The harmonic-sine series expansion for a function in two-dimensional space is composed of a harmonic part and an inner part. The harmonic part is the solution of the Laplace equation with prescribed boundary values of this function. The inner part is the function from which the harmonic part has been subtracted; thus it has zero boundary values and can be easily expanded by the double Fourier sine series. Using this expansion, they have shown that only simple operations are needed to solve the Laplace, Poisson, and Helmholtz equations with a given boundary condition. As a first step to the construction of the spectral limited-area model, they applied the harmonic-sine series expansion to the partitioning and reconstruction of wind fields in a limited area. Results based on real-data testing showed that this method is considerably more accurate than methods available in the literature.

Improvement of the MM4 Model

Georg Grell (long-term visitor, University of Washington) has made several notable improvements on the MM4. A generalized nested-grid capability has been developed which allows for multiple nest levels as well as overlapping nests. A highly accurate monotone interpolator was used for interpolations between various nested grids. The numerics of the model was improved to include the choice of Smolarkiewicz's monotone positive definite advection scheme for the mass fields and a third-order-accurate Adams-Bashford time integration scheme for the momentum fields. Grell also developed an efficient cumulus parameterization technique that includes treatment of convective-scale downdrafts and an Arakawa-Schubert type stability closure. A version of the scheme also accounts for shallow, nonprecipitating convection. The improved model is fully multitasked, and has been tested successfully with two levels of nesting on an explosive cyclogenesis case observed during ERICA.

Further Development of the Clark Model

Hall and Clark continued the development of new features within their nonhydrostatic mesoscale model. Spherical coordinates were added to allow nesting within general circulation models (GCMs) as well as use of certain types of mesoscale initialization packages. The lateral boundary conditions were improved to eliminate anomalous structures in vertical velocity and vorticity near inflow regions over complex terrain. This new adjustment scheme also allows the boundary conditions to be time dependent and bring new information into the model domain. An Ekman-type layer was added to the initialization scheme of the model to allow for a reasonable initial balanced state in cases with surface friction. The arrival of the Y-MP has required considerable modifications to the model, such as adding random input/output (I/O) to some of the model's data flow. Parallel processing and further improvements in I/O are continuing.

Adaptive Grid-Refinement Technique

Spatial and temporal resolution has always been limited in atmospheric models. To address this problem, brought about by finite computer speed and memory, Skamarock and Klemp have continued model development based on adaptive grid-refinement solution techniques. The adaptive method they employ involves nesting fine grids based on truncation error estimates in the evolving solution. These techniques provide comprehensive grid-nesting capabilities that include multiple levels of refinement and multiple, overlapping, and arbitrarily oriented fine grids on any refinement level. The model is adaptive because the grids can be placed and removed automatically.

Skamarock and Klemp are continuing the development of a three-dimensional nonhydrostatic adaptive model. Robust boundary conditions for the fine grids are a critical component in the adaptive grid method. Several different sets of boundary conditions have been considered, and a reasonably robust set has now been incorporated into the three-dimensional model. During model testing and development, Skamarock and Klemp have made several advances in numerical methods for solving the elastic nonhydrostatic equations. First, they have altered the buoyancy computations such that the nonhydrostatic models can now be integrated as efficiently as hydrostatic models with the same spatial resolution. With this development, the nonhydrostatic model has been used in a study of large-scale baroclinic waves by Snyder, Skamarock, and Rotunno. Skamarock and Klemp have also developed an efficient sound-wave filter that does not adversely affect other modes in the system, such as gravity waves, and permits the removal of other ad hoc filters from the model. Several other modeling groups outside of NCAR now use the new filter.

Plans have been finalized for building a general adaptive grid interface for three-dimensional atmospheric models. The interface will be constructed by Skamarock and Ming Xue (Center for the Analysis and Prediction of Storms, or CAPS, University of Oklahoma) and will initially be tested by NCAR, CAPS, and the National Center for Supercomputing Applications (Robert Wilhelmson and Louis Wicker). It will be available to any interested atmospheric modeling group after this test period.

Improved Numerical Methods for Atmospheric Modeling

Smolarkiewicz and Len Margolin (Los Alamos National Laboratory) developed a new option for the MPDATA family of nonlinear schemes originated by Smolarkiewicz. MPDATA solves iteratively an advection-diffusion transport problem in arbitrary geometry. The basic MPDATA (two iterations) is strictly sign-preserving and second-order-accurate for incompressible flows. The optional enhancements include schemes for compressible flows, strictly monotone algorithms, and the algorithm of an enhanced accuracy which exhibits a third-order convergence rate in the constant coefficient limit. The new result of Smolarkiewicz and Margolin is a compact-stencil option of the third-order scheme. This algorithm implements finite difference operators of the radius of influence characteristic of the second-order schemes; however, it offers significantly improved accuracy. Due to its compactness, the new algorithm is particularly attractive for massively parallel computations, arbitrary Lagrangian-Eulerian models for fluids, and large dynamic codes with advanced input-output schemes.

Smolarkiewicz and Philip Rasch (CGD) have developed a general formalism allowing for semi-Lagrangian representation of an arbitrary Eulerian transport algorithm. This formalism, originating from basic principles for differential forms, exposes the degrees of freedom and the richness of options available for solving the transport problem in an arbitrary geometry. The virtue of this method is that it allows straightforward implementations of a variety of one-dimensional transport techniques without degrading the formal accuracy of their constant coefficient limits. In particular, the approach is well suited for applications with advanced monotone transport techniques. Using an idealized test problem for the transport on the sphere, they compared the accuracy and efficiency of selected Eulerian and semi-Lagrangian advection schemes and demonstrated the versatility of the formal approach. The formalism may be easily generalized on an arbitrary set of dynamic equations for fluids. This latter point has been demonstrated by Smolarkiewicz within a framework of a semi-Lagrangian solver for the stratified hydrostatic fluid flow over a two-dimensional mountain.

The Smolarkiewicz and Rasch theory of semi-Lagrangian transport schemes has led to the development of a class of monotone (nonoscillatory) interpolation schemes convenient for application to a variety of problems arising in computational fluid dynamics. These interpolators derive from the flux-corrected-transport finite difference advection schemes. Smolarkiewicz has shown that any known dissipative advection algorithm may be implemented as an interpolation scheme. The resulting interpolation procedure retains the formal accuracy of the advection scheme employed and offers such attractive computational properties as preservation of a sign or monotonicity of the interpolated variable. The derived class of interpolators consists of schemes of different levels of accuracy, efficiency, and complexity, reflecting a variety of available advection schemes. Grell and Smolarkiewicz tested the monotone interpolators in the context of a nested-grid mesoscale weather prediction model. The preliminary tests have shown considerable improvements in the prognosis due to the preservation of monotonicity of the variables interpolated between coarse and fine meshes.

Convective and Cloud Parameterizations

Momentum transport is a nonisotropic and regime-dependent process that is not represented in existing convective parameterization schemes. Moncrieff has been conducting studies designed to produce new dynamically based parameterization methods that emphasize the feedback influences of organized convective systems. Moncrieff has developed archetype models that represent the mass and momentum transports by MCSs and related forms of organized convection. Transports that agree well with observed and modeled data sets have been represented in terms of a nondimensional ratio of the height, integrated pressure change across the system, and the propagation speed. The amplitude of the convective tendencies in the large-scale equations (closure) is specified by using methods consistent with mass-flux types of parameterization schemes. Studies are being designed to test the large-scale impact of convective momentum transport. The theory is being further developed in cooperation with Peter Bannon and Ping Liou at Pennsylvania State University (application to quasi-geostrophic models) and Akio Arakawa, Michio Yanai, and Xiaoqing Wu at UCLA (convective ensemble parameterization).

In cooperation with Martin Miller (visitor, European Centre for Medium-Range Weather Forecasts, or ECMWF, Reading, England), Moncrieff is introducing dynamical models into the Schneider and Lindzen type of momentum parameterization scheme. The approach is to use analytical models to improve the physical realism of representations of cloud–mean momentum with particular regard to the role of the pressure field. Emphasis is on convection in highly sheared flow (values of the convective Richardson number O[1] or less). The work is motivated by the sensitivity of GCMs to momentum transport, particularly in regions where the vertical shear is large. Preliminary analysis shows that this has the potential of helping reduce the tropical wind errors in the ECMWF model.

The success of a convective parameterization scheme in replicating an observed flow is difficult to measure in larger-scale models due to the presence of other factors, such as initialization errors and the parameterization of other physical processes (e.g., radiation, boundary layers) that can effect the simulation directly. Parsons and Kun Gao (Hangzhou University, PRC) have employed a unique and quantitative approach to evaluating convective parameterization schemes. They used hydrostatic simulations of the 10–11 June PRE-STORM squall line and simulations from a cloud model with essentially the same initialization as the hydrostatic model but with a finer grid that actually resolves individual convective cells. If the parameterization is working correctly, then their hydrostatic simulations should be nearly identical to their averaged cloud model flows. Parsons and Gao found that the hydrostatic model with an explicit scheme and a relatively large grid spacing produces a reasonable representation of many aspects of squall line structure but with a time scale that is far too slow. When they employed just the Fritsch-Chappel scheme, the time scale of the simulation improved, but the mesoscale features were not well represented. Their joint use of the parameterization and an explicit scheme in the hydrostatic model improved the representation of both the time scale and mesoscale structure of the squall line. However, this simulation also produced some regions of anomalous convection due to an inaccurate representation of the interaction between the cold pool and the vertical shear. They are currently working on methods to improve the triggering of convection within parameterization schemes.

Moncrieff, Gao, Da-Lin Zhang, and Han-Ru Cho (both of the University of Toronto, Ontario, Canada) have completed a study of the momentum transports in this same PRE-STORM squall line. They focused on the generation of momentum on the scale O(100 km) as produced in the MM4 regional model using both parameterized and resolved heating. In agreement with observations, the line-normal component of momentum transport was shown to be countergradient and the line-parallel component downgradient. This study demonstrates the importance of the downdrafts in the overall transport of momentum.

One of the major problems with the simulation of mesoscale weather systems is with the application of convection-parameterization schemes designed for coarse-grid resolution (100-km) studies to mesoscale models with grid resolutions as fine as 10 km. With the latter resolution, there is no clear separation of scale between the mesoscale and convective-scale motions. To investigate this problem, Weisman, Klemp, and Skamarock have completed a set of idealized squall-line simulations using a two-dimensional nonhydrostatic cloud model in which the resolution is varied between 1 and 8 km. They have now systematically documented the variation in model results as the resolution is decreased, and have been able to identify more specifically the physical processes that are not properly represented with coarser resolution. They find that the coarse-resolution simulations are able to replicate many of the key features of the fine-scale simulations, including the effect the convection has on the larger-scale environment, but that the time scale of the evolution is much slower than in the finer-scale simulation. They also find that this slower evolution results primarily from the inability of the coarse-resolution simulation to reproduce properly the circulation generated by the convectively produced cold pool. This finding leads them to believe that convection-parameterization schemes that are designed for 10-km resolution mesoscale models may need only to replicate convectively produced cold-pool characteristics for the mesoscale model to replicate properly the evolution of mesoscale convective systems. This work is currently being extended to consider the effect of grid resolution on three-dimensional convective systems.

Heymsfield and Leo Donner (NCAR affiliate scientist from the University of Chicago) continued their work on developing a cirrus cloud parameterization scheme for use in GCMs. They developed and tested a scheme for decreasing the ice water content in evaporative layers near the bases of cirrus, with the additional water vapor supplied to the environmental air. The distance over which cirrus particles persist in evaporative zones was found to decrease rapidly with decreasing temperature for a given relative humidity. Work has begun on implementing this scheme in the NCAR community climate model.

Experimental Analysis and Forecast Activities

Real-Time Convection Forecasting

Crook adapted the Clark mesoscale model to run on a Stardent workstation to assist with the Research Application Program's summer nowcasting project. In 1990 the model was run in a two-dimensional mode, so that techniques that could be used in future three-dimensional systems could be easily tested. During the field phase, soundings could be taken anywhere in the observational network and inserted in the model. Boundary-layer convergence zones could also be inserted in the model to determine whether a specified lifting was capable of producing deep convection. One of the results from this initial test season was the importance of obtaining an accurate measure of the horizontally averaged moisture distribution. On one day in which 50-dBZ cells developed, the model failed to predict convection because the sounding ascended in a dry pocket of the boundary layer.

Real-Time Airflow Analysis from Doppler Radar

Tuttle has transferred and optimized the TREC software to run in real time on a Stardent workstation. During the 1990 summer field program conducted by the Research Applications Program (RAP), data from NCAR's Mile High Radar were transferred to the Stardent, where TREC was applied to the data and the resulting vectors interpolated to a Cartesian grid for display. The time lag from data collection to vector display was 5–10 min depending upon system load. Although TREC was operational only toward the end of the experiment, its utility was demonstrated by providing near real-time mesoscale wind information out to ranges of 60–70 km.

Aircraft Data Analysis

Work on a new approach for removing position bias from aircraft inertial navigational systems (INS) has been completed by Fankhauser and Robin Vaughan in collaboration with Rodi. Aircraft distance measuring equipment (DME) data are used to update position, velocity, and wind measurements from the INS measurements. Data from conventional single-channel DME sets, suitably calibrated, are shown to be adequate to resolve the Schuler oscillation and correct INS positions to better than 1 km accuracy. DME has the advantage over other conventional instruments in that it is almost universally available, reliable, and very accurate. The regression technique used does not require multiple DME receivers or station switching and involves few restrictions on the collection of the data. The analytical model used to express the error in horizontal position was generalized through application of a spline fit vs. a sinusoidal function as was used in previous work. Comparisons with other navigation systems (interferometer and LORAN) demonstrate the method's skill in resolving INS errors. Intercomparisons among several research aircraft flown in CINDE support the method's usefulness in correcting biases in INS data, and the technology has been passed on to the Research Aviation Facility and the Research Applications Program to be used in renavigating aircraft tracks flown in the HaRP and WISP experiments.

Forecast Instructional Materials

Parsons has contributed to a *Manual on the Interpretation of Satellite and Radar Imagery* published by the European Space Agency. The intent of the manual is to allow forecasters to take advantage of the wealth of convective and mesoscale information in satellite and radar imagery to improve the forecasting and nowcasting of many weather events not well predicted or well resolved by current forecast models. The use of this imagery is rapidly becoming more relevant with the advent of new observing systems and the increased use of regional models. Parsons is a collaborating author of a chapter on convection. The manual will be used in the training of forecasters in Europe, and a condensed version will be available for use in participating forecast offices.

The Cooperative Institute for Meteorological Training and Applied Research (COMET) specifically addresses the need to improve forecaster training as new mesoscale data sources become operational. A major part of COMET training is interactive computer-based learning modules that address the use of the new data sets for specific forecast problems. As part of a separate NOAA training initiative, Szoke has developed two training manuals addressing the mesoscale structure in a winter-storm case and a summer case of tornadogenesis. In cooperation with NOAA's FSL, Szoke has established ties with COMET to begin developing these two manuals into training modules for COMET.

Experimental Forecast Center

NCAR, NOAA, and the National Weather Service (NWS) have increased their effort to define the experimental forecast center (EFC) concept and integrate it into the plans of NCAR and STORM. EFCs address the need for putting the research meteorological community into closer contact with the operational community. This is of the upmost importance in the 1990s if the operational community is to benefit properly from a number of newer data sources that will become available to operations. At the center of the EFC concept is the establishment of research/forecaster positions, where a researcher, active in addressing applied mesoscale problems, is also fully qualified to perform the duties of an NWS forecaster. Szoke has helped establish the EFC in Boulder-Denver, having become qualified to issue forecasts at the NWS office in Denver. He commits about 30% of his time as part of the Denver NWS operational forecast staff. In addition, he has taken an active role in the planning of EFCs for STORM.

Instrumentation and Interpretation of Observations

Cooper and Diana Rogers (ATD) investigated a technique that could provide an alternate method for the measurement of various fluxes of trace constituents in the atmosphere. The technique is based on the intermittent collection of samples: Each sample is collected rapidly so as to represent conditions averaged over a small distance, but the samples may be separated by much larger distances without losing significant information for a particular sampling length (or time). The technique was evaluated by comparing results that would have been obtained in this way to those obtained by conventional methods, with satisfactory results. A sampling system based on these principles was designed and will be tested in the coming year. If demonstrated feasible, this approach may make it possible to measure the fluxes of a number of new constituent species in the atmosphere without the need to develop fast-responding chemical sensors for those constituents.

Lenschow, in collaboration with Michael Raupach (CSIRO, Canberra, Australia), has studied the problem of frequency attenuation of species concentration in tubes used for ducting air from a sampling location to a sensor. A simple theoretical model was verified with laboratory experiments using various tube geometries carried out by Lenschow while visiting CSIRO in Australia. The results indicate that for most flux measurement applications, as long as the flow in the tube is fast enough to be turbulent, the attenuation in the tube is not likely to be a significant source of error.

Lenschow and Leif Kristensen (NCAR affiliate scientist, from Risø National Laboratory, Roskilde, Denmark) have continued their work on estimating errors in measurements of statistical moments in the atmosphere. They have developed expressions for both random and systematic errors in measurements of second-, third-, and fourth-order moments due to the finite length of the measurement sample. Kristensen has also estimated the error contributed by tapering the ends of time series on spectral estimates, and evaluated the effects of various tapering windows that have been used or proposed for spectral analysis.

A new instrument for the detection of cloud condensation nuclei (CCN) was developed under the direction of Cooper and Gabor Vali (University of Wyoming) at the University of Wyoming with partial support from MMM. This instrument was tested on the ground and in the air during the past year, and is planned for operational use during the coming year. It provides a new capability that is important to the further development of studies related to the formation of CCN and their impacts on the earth's radiation budget.

Lawson is collaborating with Rodi on the development of a new in situ airborne thermometer, which was designed to have fast response and to prevent sensor wetting in clouds. The design was based on calculations carried out with a numerical model which simulates the flow field around airborne probes. Preliminary flight tests on the NCAR King Air near Corpus Christi, Texas, and on the NCAR Electra during HaRP verify that it has better time response than airborne thermometers currently in operational use. An evaluation of the susceptibility of the new thermometer to wetting in cloud is currently in progress.

Paluch, Cooper, and Karen Miller investigated some anomalies in past wind measurements from the NCAR research aircraft. They developed new processing techniques that considerably improve the performance of the wind sensing systems, particularly in turbulence or during turns. These techniques are being used for the processing of data from HaRP, and were also used in the analysis of FIRE aircraft data. They have led to considerable improvement in the quality of the measurements for these programs.

Lenschow has collaborated with Erik Miller and Richard Friesen (both of ATD) in evaluating the performance of the radome air motion sensing systems now used on the NCAR aircraft. Through intercomparisons of the new system mounted on one aircraft with the previously used vane and differential pressure probe systems mounted on two other aircraft flying in close formation with the first, they showed that the various techniques give nearly identical results.

Lenschow also collaborated with Ronald Schwiesow and Vincent Glover (ATD) in demonstrating the usefulness of the NCAR Airborne Infrared Lidar System (NAILS) for measuring cloud-top height and aerosol layers above the boundary layer. They showed that sloping layers above the marine stratiform region off the coast of Southern California can generate horizontally inhomogeneous structure in the region where they intersect the cloud layer.

Field Projects

Office of Field Project Support

The Office of Field Project Support (OFPS), headed by Richard Dirks, supported four field program activities over the past year: scientific planning and implementation of the STORM Program, research coordination for the Genesis of Atlantic Lows Experiment (GALE), operational planning and coordination for HaRP, and scientific planning for the Convection and Precipitation/Electrification (CaPE) experiment.

STORM Program

The interagency STORM Project Office (SPO) was established in OFPS in 1988. McGuirk is the STORM data manager and is working with the Scientific Computing Division and Unidata along with various federal agencies in setting up the STORM data management system. A draft STORM data management plan has been prepared and is under review. Formal arrangements have been made with Unidata and NOAA's FSL for the real-time distribution of wind profiler data to universities, with NOAA's Operational Support Facility for the recording of full-volume NEXRAD data, and with NOAA's National Climatic Data Center and FSL for developing an on-line data access capability for STORM data. These are the first steps in the implementation of the distributed STORM Data Management system. Scientific planning for STORM included the participation by Richard Dirks and John Cunning on an interagency working team established by the Subcommittee on Atmospheric Research of the Committee on Earth and Environmental Sciences. This working team, led by William Hooke (NOAA), prepared a national mesoscale research plan entitled, "Predicting Our Weather: A Strategic Plan for the U.S. Weather Research Program." The plan accompanies a multiagency funding request for FY 92.

Planning for the STORM I field experiments continues. Approximately 75 scientists attended a STORM I Winter/Spring Field Experiment Workshop in

Boulder in June 1990. The decision was made to delay the STORM I Winter Phase Experiment until January 1994; however, a systems test with a limited research focus on fronts will be conducted during a six-week period in February-March 1992. An experiment design for the STORM-FEST (Fronts Experiment Systems Test) is in preparation under the leadership of Cunning. Logistical planning and facility coordination for STORM I field experiments is headed by James Moore (RAP), the STORM facility coordinator.

The various STORM working groups have worked with the SPO to develop a number of plans and working documents. The Hydrology Working Group, chaired by James Smith (Princeton University), has prepared a draft STORM hydrology plan which was presented to the research community at the American Geophysical Union Meeting in December 1990. An ad hoc Radar Working Group, chaired by Peter Ray (Florida State University), has proposed alternative scans for the NEXRAD radars during STORM. L. Jay Miller was a major contributor to this effort. These scans are being reviewed by the OSF and the NEXRAD Program Council. Michael Glantz (CGD) organized a workshop on the socioeconomic aspects of mesoscale weather and improvements in mesoscale prediction. This workshop should lead to the development of a socioeconomic research plan for the U.S. Weather Research Program. A preliminary plan for experimental forecast center (EFC) activities in STORM I is being prepared by the EFC Working Group led by John McGinley (NOAA FSL) and Carl Kreitzberg (Drexel University). Szoke has been a key contributor to this plan through his work with the Denver NWS Forecast Office. Plans prepared by the Data Assimilation Working Groups, led by Thomas Schlatter (FSL), and Ronald McPherson (NMC), are being reviewed by the National Academy of Sciences Committee on Meteorological Measurements, Analysis, and Prediction Research.

These plans provide the components of the total STORM Program. Elements of the activities will begin in FY 91 with reprogrammed funds, and a broad implementation is expected in FY 92 with new funding increments.

GALE

OFPS continues to serve as the GALE Project Office. Services include the archiving and distribution of GALE radar data and coordination of research activities. A revised radar data set was prepared for a new GALE compact disk. Dirks and Joachim Kuettner served as guest editors for a special GALE issue of the *Monthly Weather Review* published in February 1990. Planning for a GALE scientific workshop folded into plans for the 1st International Symposium on Winter Storms to be held concurrently with the American Meteorological Society annual meeting in January 1991. Dirks is a coconvener of the symposium.

HaRP

During the summer of 1990, Cooper, Moncrieff, Clark, Knight, Lenschow, L. Jay Miller, Rasmussen, Smolarkiewicz, Paluch, Tuttle, and Karen Miller collaborated with scientists in ATD and outside NCAR to carry out the field phase of HaRP, a study of rainbands and associated mesoscale and microscale phenomena. This experiment exploited the favorable experimental conditions present near the island of Hawaii, where interactions between the trade winds and topography produce frequent and predictable rainbands ideally suited to observation by radars and aircraft. The observations were made to address a broad range of topics; including the effects of topography on the stratified trade wind airflow and the production of lee vortices by the island, the structure and dynamics of individual cells in the rainbands, and microscale phenomena such as precipitation formation and entrainment. The experimenters used closely integrated theoretical, numerical, and observational approaches.

OFPS participation in HaRP included contributions to operational planning and logistical arrangements. Coordination was provided with the NSF and university scientists; assistance was given to ATD staff in organizing the Field Analysis Center; and arrangements were made for special observing facilities including drifting buoys, shipboard soundings, downstream land-based soundings, and boundary-layer profiling.

Two NCAR C-band radars, the NCAR Electra, and 50 NCAR portable automated mesonet (PAM) stations were deployed from 16 July to 25 August near Hilo, Hawaii. The radars and PAM stations provided documentation of the airflow near and over the island, and the aircraft measured the upwind and downwind flow patterns and penetrated the rainbands. The maritime clouds had good radar detectability, and the rainbands were located consistently within about 20 km of the radar sites, so the structure of the rainbands has been documented with unprecedented resolution and representativeness.

Numerical models also played an important role in this experiment. They identified important features of the mesoscale dynamics to be further investigated, and provided hypotheses for important aspects such as the nature of the downslope flow and the character of the entrainment process in these clouds. Models were used not only during preparation for the experiment, but also during the field phase to predict the likely nature and evolution of the rainbands and airflow and thus helped focus the observations on critical aspects of the experimental hypotheses.

Because of the excellent location and facilities, the experimental methodology and instrumentation were also evaluated. This included the acquisition of data for the verification of thermodynamic retrievals, remote detection of hydrometeor size spectra with in situ verification, and studies of techniques for measuring temperature and humidity in cloud. Tests of new sensors for chemical analysis and for measurement of the CCN activity of evaporated cloud droplets were been conducted.

The collected data will be used to determine the kinematic structure and dynamic processes influencing the rainbands to test hypotheses that relate observed mesoscale features to forcing mechanisms and responses, and to evaluate the roles of various forcing mechanisms in determining the size, location, strength, motion, and evolution of the rainbands and of individual cells. Because of the favorable weather conditions during the experiment and the high quality of the data, the observations should provide an excellent basis for these planned investigations.

WISP

The Winter Icing and Storms Project (WISP), initiated by RAP, began its first field phase in FY 90. The project is aimed at improving the detection and forecasting of conditions conducive to aircraft icing, and furthering the understanding of the structure of winter storms.

WISP is a joint NCAR-NOAA-university project sponsored by NSF and the Federal Aviation Administration, coordinated principally by RAP, to study the production and depletion of supercooled water in winter storms and the associated icing hazards to aircraft. MMM participation in this program has focused on improving the scientific understanding of the dynamical and microphysical processes involved, through documentation of the microphysical characteristics and kinematic structures and through modeling of the dynamical evolution and the formation of precipitation in these storms. Participants from MMM included Rasmussen, Moncrieff, Cooper, Lawson, Crook, Marcia Politovich, Szoke, and Murakami. Observations from the first field phase in 1990 demonstrated that the collection methods and flight plans are feasible, verified that many of the remote sensing instruments provide reliable information, showed that a wide range of droplet concentrations and ice concentrations occur in local winter storms, and found cases in which large supercooled droplets caused anomalously large effects on the performance of aircraft in this area. Good studies of upslope storm conditions have shown that severe icing conditions may occur in such storms, particularly near cloud tops, and that regions with supercooled water and icing conditions may be quite widespread. Simulations of these storms have supported the importance of the Denver Cyclone in the local dynamics of winter storms and emphasize the significance of gravity waves that form in response to the local topography in establishing the mesoscale vortex in the lee of the Palmer Divide. MMM also played an active role in the forecast support for the WISP FY 90 efforts and participated in the experimental forecasts of icing and snowfall issued by the FSL as part of WISP. MMM will have continued involvement in the next field phase planned for 1991.

CaPE

Several division personnel (Barnes, Breed, Dye, Fankhauser, Foote, Szoke, and Wade) have been involved in scientific planning for the CaPE experiment to be conducted in the Cape Canaveral area of central Florida during portions of July and August 1991. Research objectives of CaPE include identifying the relationships among the evolving wind, water, and electric fields within convective clouds; employing real-time data assimilation to enhance 2- to 12-h numerical forecasts of wind, clouds, and thunderstorms; improving techniques for making short-period forecasts (nowcasts of $\leq$ 2 h) of convection initiation, downbursts, and tornadoes; and characterizing precipitation particles and remotely estimating rainfall.

Participation to date has included contributions to a scientific overview document, preparation and submission of requests for research aircraft support, design of research flight plans, and site visits to determine locations for operations centers and surface meso- and upper-air networks. Particular emphasis has been directed toward establishing the goals of the electrification effort, which involves several investigators and a rather diverse complement of instrumentation systems. Flight planning, operational support, and quality control of the electric field measurements for the sailplane and the King Airs are specific tasks planned for the field. These scientists will play key operational roles in the field phase of the experiment as well.

OFPS staff also participated in the planning for the CaPE Experiment. McGuirk prepared a preliminary plan for CaPE data management. The OFPS staff will carry out the data management support during the experiment, working closely with ATD's Research Data Program staff. The role of the Melbourne, Florida, NWS Forecast Office in CaPE has been strengthened, and plans to establish a joint NOAA/NASA/U. S. Air Force experimental forecast center in time for CaPE are being coordinated by OFPS.

TAMEX

Trier completed development of software to unpack the field data from the ground-based Doppler radar owned and operated by the Chinese Aeronautics Administration (CAA), Republic of China, and to convert these data to Universal Doppler-radar format. The data from the CAA radar are the last of three ground-based Doppler-radar data sets to be processed from TAMEX. Trier and L.

Jay Miller conducted quality checks of the CAA data that uncovered data quality problems. The most serious problem was the presence of data gaps in regions of high radar reflectivity that appear to have resulted from design flaws in the CAA radar. Trier also published an NCAR Technical Note that was distributed to TAMEX investigators containing low-elevation Doppler-radar scans from the TOGA radar, and 24-h rainfall derived from surface reports.

The TAMEX U.S. Project Office, headed by Kuo, continued to provide service to U.S. scientists in the area of research coordination and data management. During FY 90, the project office published a number of TAMEX newsletters which contained information concerning research highlights, meeting information, and updates of data management issues. The Workshop on TAMEX Scientific Results was conducted in late September, and was attended by 60 participants, including 30 scientists from the United States, 20 scientists from Taiwan, and 10 scientists from the PRC. A preprint volume containing 36 papers was published.

After the workshop the TAMEX U.S. Project Office hosted several visitors from Taiwan and from the PRC. This opportunity allowed the visiting scientists to interact with U.S. scientists and with one another directly. These discussions led to collaborative research projects on Mei-Yu fronts and precipitation systems embedded within the fronts.

In the area of data management, Sue Chen completed the quality control on all the TAMEX special rawinsonde data. Additional rawinsonde and pibal data were provided by China. These data were also quality checked and corrected. The final data sets were archived at the NCAR Mass Storage System and made available to all the TAMEX investigators. To assist the users of the TAMEX data, Chen and Aubrey Schumann (ATD) published an NCAR Technical Note, *TAMEX Conventional Data User's Guide*. Chen is currently processing the conventional radar data and performing four-dimensional data assimilation of all the TAMEX special observations from various platforms. These data will also be provided to all the investigators when completed.

Interactive Distributed Computing

The MMM Division continued to provide community support for the NCAR Graphics Package running on VAX/VMS computers. The VAX/VMS Version 3.0 of the NCAR Graphics package was developed and distributed. The new Version 3.0 has a new structure, new implementation procedures, new graphics utilities, a new interactive translator, and numerous bug fixes. The VMS version, ported from SCD's 3.00 UNIX Version, is similar to the Unix version while retaining features from past VMS versions. William Boyd coordinated the development of the new version and worked on its implementation with Paul Pinkney and Chris Phillips (both student assistants, University of Colorado). Patricia Waukau wrote the VMS-specific documentation. She also coordinated and worked on the distribution of the package with Alfred Criswell. Boyd provided consulting assistance for its installation and use.

Klemp and Boyd supervised the continuing development of SIGMA, a software package for the interactive analysis and graphical display of large data sets. Conpack, the new color contouring graphics utility included in Version 3.0 of the NCAR Graphics Package, was integrated into SIGMA. The structure of netCDF data sets was established by a group of scientists and the SIGMA developers. A concise FORTRAN callable library was written to help scientists generate netCDF data sets from their own code. SIGMA was modified to process these data sets. Most of these activities were performed by Pinkney. The VAX/VMS version of SIGMA was ported to the UNIX environment. As part of the port the interactive translator included in the VAX/VMS version of NCAR Graphics was ported to the UNIX environment by Phillips. Boyd worked with SCD to specify the requirements for an interactive translator to be included in the UNIX version of NCAR Graphics. This translator, developed by SCD, will be included in the 3.01 UNIX Version of NCAR Graphics. The UNIX version of SIGMA was distributed to several university scientists through UCAR using a beta test agreement.

Klemp and Boyd supervised the continuing development of PolyPaint, a graphics package used to render large complex data sets in three dimensions. Matthew McIrvin (summer visitor, College of William and Mary) added a number of new features to PolyPaint: a cutting-plane and cross-section capability, the ability to map color representing one data field onto a surface generated from another data field, and the ability to render a shadow cast by an object onto a plane. Phillips added the ability to rotate several objects at once. Reading and writing data using netCDF were incorporated into PolyPaint to make the package more machine-independent. PolyPaint is used for exploratory data analysis and for communicating ideas. The latter activity requires editing and annotating images. Pinkney wrote a raster image editing package. The Raster Editor has a number of capabilities including interactive annotation, positioning of objects, color table editing, color area fill, and zoom.

The Joint Living Laboratory Project with Digital Equipment Corporation continued in 1990. Through this project, the division acquired a DECstation 5000, two 1Gbyte disk drives, and software. DEC and MMM collaborated on the further integration of existing analysis graphics software packages. Raymond George from DEC and Boyd developed a prototype design to integrate SIGMA, PolyPaint, the Raster Editor, and the netCDF data management software. In preparation for a future integration, netCDF was used to input data into SIGMA and PolyPaint. The user interfaces to SIGMA, PolyPaint, and the Raster Editor were also redesigned to support a common user interface. TAE+ (Transportable Applications Executive) and AVS (Application Visualization System) were evaluated as tools to integrate the software into one easy-to-use data analysis environment.

Staff and Visitors

Division Director's Office

Toni Biter
Hope Hamilton
Josephine Hansen
Philip Merilees (director)
Kathy Morgan
John Wyngaard (deputy director)

Internal Computer Resources

William Boyd
Alfred Criswell
Patricia Waukau (systems manager)

Office of Field Project Support

Mark Bradford
Wayne Brazille (on assignment from NOAA)
John Cunning (on assignment from NOAA)
Richard Dirks (manager)
Wanda Gilmer (on assignment from NOAA)
Joachim Kuettner (long-term visitor)
David McGuirk (on assignment from NOAA)
William Roberts (long-term visitor)
Kenneth Scully
Linda Yellin

Mesoscale Prediction Section

Jeremy Asbill (student assistant)
Gary Barnes
Twyla Barrett
Stanley Benjamin (to 4/22/90)
Edith Burns
Sue Chen
Jimy Dudhia (long-term visitor)
David Gill
Georg Grell (long-term visitor)
Philip Haagenson
Joseph Klemp (section head; acting director from 10/1/90)
Ying-Hwa Kuo
Simon Low-Nam
David Parsons
Chris Phillips (student assistant)
Paul Pinkney (student assistant)
Richard Rotunno (acting section head from 10/1/90)
William Skamarock (long-term visitor)
Gregory Stossmeister
Edward Szoke
Stanley Trier
Wei Wang (long-term visitor)
Morris Weisman
Edward Zipser (leave of absence from 1/17/90)

Convective Meteorology Section

William Anderson
Roelof Bruintjes (long-term visitor)
Terry Clark
Andrew Crook (50%)
Joseph Doetzl (student assistant)
James Fankhauser
G. Brant Foote (on assignment to RAP from 1/1/90)
Wojciech Grabowski (long-term visitor)
William Hall
Andrew Heymsfield
Sudie Kelly
Margaret LeMone
L. Jay Miller
Mitchell Moncrieff (section head)
Paula Parsley
Roy Rasmussen (25%)
Piotr Smolarkiewicz
Patrick Tovaas (student assistant)
John Tuttle (50%)
Robin Vaughan (60%)
Charles Wade (50%)

Microscale Meteorology Section

Anders Andrén (long-term visitor)
Keith Barr (student assistant)
Daniel Breed
William A. Cooper (50%)
John DeSanto (student assistant)
James Dye (67%)
Kirsten Ferris
Regina Gregory (20%)
Jackson Herring
Albertus Holtslag (long-term visitor)
Frances Huth
Robert Kerr
Charles Knight
Nancy Knight (long-term visitor)
Paul Lawson (long-term visitor)
Donald Lenschow (section head; 67%)
Karen Miller
Larry Miloshevich
Chin-Hoh Moeng
Ilga Paluch

Joanne Parrish
Marcia Politovich (25%)
Jeffrey Weil (long-term visitor)

Affiliate Scientist

Leif Kristensen (Risø National Laboratory,
Roskilde, Denmark)

Visitors

Pinhas Alpert; Tel Aviv University, Israel; June 1990 to July 1990; Mesoscale Prediction Section

Jimmy Altura; University of Hawaii; July to August 1990; Convective Meteorology Section and Microscale Meteorology Section

Anders Andren; Uppsala University, Sweden; April 1990 to April 1991; Microscale Meteorology Section

Michael Bannister; New Mexico Institute of Mining and Technology; May 1990 to June 1990; Mesoscale Prediction Section

Todd Bell; University of Colorado; May 1990 to May 1991; Microscale Meteorology Section

Warren Blier; University of California, Los Angeles; June 1990 to August 1990; Mesoscale Prediction Section

Howard Bluestein; University of Oklahoma; June 1990 to August 1990; Mesoscale Prediction Section

Frederick Carr; University of Oklahoma; June 1990 to July 1990; Mesoscale Prediction Section

Qiu-shi Chen; Beijing University, PRC; April 1990 to October 1991; Mesoscale Prediction Section

Shoujun Chen; Beijing University, PRC; July 1990 to August 1991; Mesoscale Prediction Section

John Clark; Pennsylvania State University; June 1990 to August 1990; Mesoscale Prediction Section

David Dempsey; San Francisco State University; June 1990 to August 1990; Mesoscale Prediction Section

Edward Driggers; University of Colorado; August 1989 to indefinite; Microscale Meteorology Section

Graham Feingold; Tel Aviv University, Israel; August 1990 to August 1991; Microscale Meteorology Section

Jean Fujikawa; University of Denver; June 1990 to August 1990; Convective Meteorology Section and Microscale Meteorology Section

Alan Gadian; University of Manchester Institute of Science and Technology, England; August 1990 to September 1990; Convective Meteorology Section

Tzvi Gal-Chen; University of Oklahoma; September 1989 to August 1990; Mesoscale Prediction Section

Patrick Gallacher; Naval Postgraduate School, Monterey, California; October 1987 to April 1990; Microscale Meteorology Section

Toshiyuki Gotoh; Nagaya University, Japan; September 1990 to October 1990; Microscale Meteorology Section

Yong-Run Guo; Shanghai Meteorological Center, PRC; July 1987 to July 1990; Mesoscale Prediction Section

Zitian Guo; National Meteorological Center, Beijing, PRC; July 1990 to June 1991; Mesoscale Prediction Section

Sandra Henry; Colorado State University; May 1989 to May 1991; Convective Meteorology Section

Thomas Hoglin; University of Colorado; October 1989 to December 1989; Microscale Meteorology Section

Song-You Hong; Seoul National University, Korea; July 1990 to August 1990; Mesoscale Prediction Section

Mary Ann Jenkins; York University, North York, Ontario, Canada; June 1990 to August 1990; Convective Meteorology Section

Teddie Keller; IBM Scientific Center, Palo Alto, California; January 1990 to January 1991; Convective Meteorology Section

John Latham; University of Manchester, England; March 1990 to April 1990; Microscale Meteorology Section

Douglas Lilly; Center for Analysis and Prediction of Storms, University of Oklahoma; August 1990 to November 1990; Mesoscale Prediction Section

Christopher Lucas; Texas A&M University; June 1990 to August 1990; Convective Meteorology Section and Microscale Meteorology Section

Matthew McIrvin; College of William and Mary; June 1990 to August 1990; Mesoscale Prediction Section

Martin Miller; European Centre for Medium-Range Weather Forecasts; Reading, England; March 1990 to April 1990; Convective Meteorology Section

Masataka Murakami; Meteorological Research Institute, Ibaraki, Japan; December 1989 to November 1990; Microscale Meteorology Section

Guan-Shu Rao; Purdue University; May 1990 to June 1990; Microscale Meteorology Section

Richard Reed; University of Washington; June 1990 to July 1990; Mesoscale Prediction Section

Rod Rogers; McGill University; February 1990 to April 1990; MMM Directors Office

Jan Rosinski; unaffiliated; March 1982 to indefinite; Microscale Meteorology Section and MMM Directors Office

David Stevens; University of Washington; May 1990 to August 1990; Convective Meteorology Section

Cynthia Twohy-Ragni; University of Washington; June 1988 to June 1990; ATD, ACD, and MMM (official visit before ASP appointment)

Edward Zipser; Texas A&M University; June 1990 to August 1990; Convective Meteorology Section and Mesoscale Prediction Section

Janet Zoch; Metropolitan State College, Denver, Colorado; June 1990 to August 1990; Microscale Meteorology Section

Publications

Refereed Publications

ANDRÉN, A., 1990: Evaluation of a turbulence closure scheme suitable for air-pollution applications. *J. Appl. Meteor.* 29, 224–239.

CARBONE, R.E., *J.W. CONWAY, N.A. CROOK, and M.W. MONCRIEFF, 1990: The generation and propagation of a nocturnal squall line. Part I: Observations and implications for mesoscale predictability. *Mon. Wea. Rev.* 118, 26–49.

______, B. FOOTE, M. MONCRIEFF, *T. GAL-CHEN, *W. COTTON, *M. HJEMFELT, *F. ROUX, *G. HEYMSFIELD, and *E. BRANDES, 1990: Convective dynamics: Panel report. Chapter 24b in *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference* (D. Atlas, Ed.), AMS, Boston, Mass., 391–400.

*CHOCK, D.P., and Y.-H. KUO, 1990: Comparison of wind field models using the CAPTEX data. *J. Applied. Meteor.* 29, 76–91.

CROOK, N.A., R.E. CARBONE, M.W. MONCRIEFF, and *J.W. CONWAY, 1990: The generation and propagation of a nocturnal squall line. Part II: Numerical simulation. *Mon. Wea. Rev.* 118, 50–65.

DIRKS, R.A., and J. KUETTNER, 1990: Editorial [The Genesis of Atlantic Lows Experiment]. *Mon. Wea. Rev.* 118, 193.

DYE, J.E., B.W. GANDRUD, D. BAUMGARDNER, *K.R. CHAN, *G.V. FERRY, *M. LOEWENSTEIN, *K.K. KELLY, and J.C. WILSON, 1990: Observed particle evolution in the polar stratospheric cloud of January 24, 1989. *Geophys. Res. Let.* 17, 413–416.

______, ______, ______, *L. SANFORD, and *G.V. FERRY, 1990: A survey of particle measurements in the Arctic from the Forward Scattering Spectrometer Probe model 300. *Geophys. Res. Let.* 17, 409–412.

GANDRUD, B.W., J.E. DYE, D. BAUMGARDNER, *G.V. FERRY, *M. LOEWENSTEIN, *K.R. CHAN, *L. SANFORD, *B. GARY, and *K.K. KELLY, 1990: The January 30, 1989 Arctic Polar Stratospheric Cloud (PSC) event: Evidence for the mechanism of dehydration. *Geophys. Res. Let.* 17, 457–460.

GAO, K., *D.-L. ZHANG, M.W. MONCRIEFF, and *H.-R. CHO, 1990: Mesoscale momentum budget in a mid-latitude squall line: A numerical case study. *Mon. Wea. Rev.* 118, 1011–1028.

GRABOWSKI, W.W., 1989: Numerical experiments on the dynamics of the cloud-environment interface: Small cumulus in a shear-force environment. *J. Atmos. Sci.* 46, 3513–3541.

______, and P.K. SMOLARKIEWICZ, 1990: Monotone finite-difference approximations to the advection-condensation problem. *Mon. Wea. Rev.* 118, 2082–2097.

GREENBERG, J.P., P.R. ZIMMERMAN, and P. HAAGENSON, 1990: Tropospheric hydrocarbon and CO profiles over the U.S. West Coast and Alaska. *J. Geophys. Research* 95, 14,015–14,026.

GULTEPE, I., A.J. HEYMSFIELD, and D.H. LENSCHOW, 1990: A comparison of vertical velocity in cirrus obtained from aircraft and lidar divergence measurements during FIRE. *J. Atmos. Oceanic Tech.* 7, 58–67.

*HECHTEL, L.M., C.-H. MOENG, and *R.B. STULL, 1990: The effects of nonhomogeneous surface fluxes on the convective boundary layer: A case study using large-eddy simulation. *J. Atmos. Sci.* 47, 1721–1741.

HEYMSFIELD, A.J., and L.J. DONNER, 1990: A scheme for parameterizing ice-cloud water content in general circulation models. *J. Atmos Sci.* 47, 1865–1877.

HERRING, J.R., 1990: Comparison of closure to spectral-based large eddy simulations. *Phys. Fluids A* 2, 979–983.

______, 1990: Utility and drawbacks of traditional approaches. In *Whither Turbulence* (J.L. Lumley, Ed.), Springer-Verlag, 70–80.

*KAIMAL, J.C., and J.C. WYNGAARD, 1990: The Kansas and Minnesota experiments. *Bound.-Layer Meteor.* 50, 31–47.

KERR, R.M., 1990: Velocity, scalar and transfer spectra in numerical turbulence. *J. Fluid Mech.* 211, 309–332.

*KEYSER, D., and R. ROTUNNO, 1990: On the formation of potential-vorticity anomalies in upper-level jet-front systems. *Mon. Wea. Rev.* 118, 1914–1921.

KNIGHT, C.A., 1990: Lagrangian modeling of the ice process: A first-echo case. *J. Appl. Meteor.* 29, 418–428.

KUO, Y.-H., and *G. T.-J. CHEN, 1990: Taiwan area mesoscale experiment: An overview. *Bull. Amer. Meteor. Soc.* 71, 488–503.

______, and S. LOW-NAM, 1990: Prediction of nine explosive cyclones over the western Atlantic Ocean with a regional model. *Mon. Wea. Rev.* 118, 3–25.

*LAFORE, J.-P., and M.W. MONCRIEFF, 1990: Reply [to "A numerical Investigation of the Scale Interaction Between a Tropical Squall Line and its Environment"]. *J. Atmos. Sci.* 47, 1034–1035.

LAWSON, R.P., and W.A. COOPER, 1990: Performance of some airborne thermometers in clouds. *J. Atmos. Ocean. Tech.* 7, 480–494.

LeMONE, M.A., 1990: Some observations of vertical velocity skewness in the convective boundary layer. *J. Atmos. Sci.* 47, 1163–1169.

*MacGREGOR, L., *H.G. MARSHALL, N.C. KNIGHT, C.A. KNIGHT, *J.C. FARMER, and *H. WESTBERG, 1990: Hailstones as cloud water composition probes: An initial assessment. *Atmos. Environment* 24A, 2247–2251.

MERILEES, P.E., and *J. PUDYKIEWICZ, 1990: Predictive meteorology in support of emergency response. In *Meteorological Aspects of Emergency Response*, M.L. Kramer and W.M. Porch (Eds.), AMS, Boston, Mass., 37–56.

MILLER, L.J., J.D. TUTTLE, and G.B. FOOTE, 1990: Precipitation production in a large Montana hailstorm: Airflow and particle growth trajectories. *J. Atmos. Sci.* 47, 1619–1646.

MOENG, C.-H., and R. ROTUNNO, 1990: Vertical-velocity skewness in the buoyancy-driven boundary layer. *J. Atmos. Sci.* 47, 1149–1162.

PARSONS, D.B., and *R.A. KROPFLI, 1990: Dynamics and fine structure of a microburst. *J. Atmos. Sci.* 47, 1674–1692.

______, *B.F. SMULL, and *D.K. LILLY, 1990: Mesoscale organization and processes. Chapter 26b in *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference* (D. Atlas, Ed.), AMS, Boston, Mass., 461–472.

*POOLE, L.R., *E. SOLOMON, B.W. GANDRUD, *K.A. POWELL, J.E. DYE, *R.L. JONES, and *D.L. McKENNA, 1990: The Polar Stratospheric Cloud event of January 24, 1989. Part 1. Microphysics. *Geophys. Res. Let.* 17, 537–540.

*REDELSPERGER, J.-L., and T.L. CLARK, 1990: The initiation and horizontal scale selection of convection over gently sloping terrain. *J. Atmos. Sci.* 47, 516–541.

*RITTER, J.A., D.H. LENSCHOW, *J.D.W. BARRICK, *G.L. GREGORY, *G.W. SACHSE, *G.F. HILL, and *M.A. WOERNER, 1990: Airborne flux measurements and budget estimates of trace species over the Amazon Basin during the GTE/ABLE-2B Expedition. *J. Geophys. Res.* 95 (D10), 16,875–16,886.

ROSINSKI, J., *B. KOPCEWICZ, and *N. SANDOVAL, 1990: Heterogeneous nucleation of ice at the liquid-liquid interface. *J. Aerosol Sci.* 21, 87–96.

ROTUNNO, R., and *M. FANTINI, 1989: Petterssen's "Type B" cyclogenesis in terms of discrete. neutral Eady modes. *J. Atmos. Sci.* 46, 3599–3604.

______, J.B. KLEMP, and M.L. WEISMAN, 1990: Comments on "A numerical investigation of the organisation and interaction of the convective and stratiform regions of tropical squall lines." *J. Atmos. Sci.* 47, 1031–1033.

SCHWIESOW, R.L., *S.D. MAYOR, V.M. GLOVER, and D.L. LENSCHOW, 1990: Intersection of a sloping aerosol layer observed by airborne lidar with a cloud-capped marine boundary layer. *J. Appl. Meteor.* 29, 1111–1119.

SMOLARKIEWICZ, P., 1990: Comment on "A positive definite advection scheme obtained by nonlinear renormalization of the advective fluxes." *Mon. Wea. Rev.* 11, 2625–2632,

______, and W.W. GRABOWSKI, 1990: The multidimensional positive definite advection transport algorithm: Nonoscillatory option. *J. Comput. Phys.* 86, 355–375.

———, and R. ROTUNNO, 1990: Low Froude number flow past three-dimensional obstacles. Part II: Upwind flow reversal zone. *J. Atmos. Sci.*, 47, 1498–1511.

———, and ———, 1989: Reply. *J. Atmos Sci.* 46, 3613–3617.

TUTTLE, J., and G.B. FOOTE, 1990: Determination of the boundary layer airflow from a single Doppler radar. *J. Atmos. Oceanic Tech.* 7, 218–232.

WEIL, J.C., 1990: A diagnosis of the asymmetry in top-down and bottom-up diffusion using a Lagrangian stochastic model. *J. Atmos. Sci.* 47, 501–515.

WEISMAN, M.L., 1990: The genesis of bow echoes: A rear-inflow induced meso-convective structure. NCAR/CT-125, NCAR Cooperative Thesis: The Pennsylvania State University and National Center for Atmospheric Research, 149 pp.

*WOFSY, S.C., *R.J. SALAWITCH, *J.H. YETTAU, *M.B. McELROY, B.W. GANDRUD, J.E. DYE, and D. BAUMGARDNER, 1990: Condensation of HNO3 on falling ice particles: Mechanism for dehydration of the polar stratosphere. *Geophys. Res. Let.* 17, 437–440.

WYNGAARD, J.C., 1990: Discussion on the potential and limitations of direct and large-eddy simulations. In *Whither Turbulence?* (J.L. Lumley, Ed.), Springer-Verlag, 369–373.

———, 1990: Scalar fluxes in the planetary boundary layer—Theory, modeling, and measurement. *Bound.-Layer Meteor.* 50, 49–75.

ZIPSER, E., *A. BETTS, *F. RUGGIERO, and *B. HINTON, 1990: Tropical Meteorology: Panel Report. Chapter 25b in *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference* (D. Atlas, Ed.), AMS, Boston, Mass., 426–432.

Other Publications

BARNES, G.M., 1990: A convective cell in a hurricane rainband. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 672–678.

BRAZILLE, W., 1990: The future of CLICOM: Applications of development. In *Proc. Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, 5–9 February 1990, Anaheim, Calif. AMS, Boston, Mass., 65–68.

BRUINTJES, B.J., and A.J. HEYMSFIELD, 1990: Observations and numerical simulations of growth characteristics of ice particles in convective clouds. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 657–658.

CHEN, Q.-S., and Y.-H. KUO, 1990: A harmonic-sine series expansion and its application to partition the observed wind into the streamfunction and velocity potential in a limited-area. In *Proc. Workshop on TAMEX Scientific Results*, 24–26 September 1990, Boulder, Colo. NSF, National Science Council of Taiwan, and NCAR, 127–138.

CHEN, S., 1990: Taiwan Area Mesoscale Experiment: Conventional Data User's Guide. NCAR Technical Note, NCAR/TN-349+IA.

CROOK, A., 1990: Numerical simulation of convective initiation along the Denver convergence and vorticity zone. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., J20–J21.

———, 1990: A numerical study of atmospheric lee vortices with a particular emphasis on the Denver cyclone. In *Preprint Vol., Fifth Conference on Mountain Meteorology*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 128–129.

COOPER, W.A., 1990: The Hawaiian Rainband Project (HaRP). In *Abstracts, Joint United States–Peoples Republic of China Workshop on Mesoscale Meteorology*, 19–21 September 1990, Boulder, Colo. NSF and NOAA, 11–12.

DAVIS, C., 1990: Cyclogenesis diagnosed with potential vorticity. Ph.D. thesis M.I.T. (Department of Earth, Atmospheric and Planetary Sciences), 194 pp.

*DeMOTT, P.J., *D.C. ROGERS, and R.P. LAWSON, 1990: Improvements to the CSU controlled-expansion cloud chamber. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 126–129.

*DETWILER, A., N.C. KNIGHT, and A.J. HEYMSFIELD, 1990: Measurement of liquid/solid mass loading in clouds. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 318–323.

DIRKS, R.A., 1990: The National STORM Program: An oppportunity for hydrologic field research. In *Proc. Fall Meeting of the American Geophysical Union*, 3–7 December 1989, San Francisco, Calif. AGU, San Francisco, Calif., 1333.

FEINGOLD, G., 1990: On the evolution of raindrop spectra and their effect on the atmosphere below cloud base: Numerical models and comparisons with observations. Ph.D. thesis Tel Aviv University (Department of Geophysics and Planetary Sciences), 159 pp.

———, *Z. LEVIN, and *S. TZIVION, 1990: The evolution of raindrop spectra below cloud base and their effect on the thermodynamic parameters and wind field. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 249–254.

GRABOWSKI, W.W., and T.L. CLARK, 1990: Cloud-environment interface instability and entrainment in convective clouds: Rising thermal calculations in two spatial dimensions. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 713–715.

*GRAVES, S.J., S.F. WILLIAMS, and *E.A. CRISWELL, 1990: An object-oriented approach to the management of meteorological and hydrological data. In *Proc. Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, 5–9 February 1990, Anaheim, Calif. AMS, Boston, Mass., 84–88.

HALL, W.D., *D. MATTHEWS, and *A. SUPER, 1990: Precipitation over the Mogollon rim of Arizona, 1990: In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 754–764.

HERRING, J.R., 1990: Spectral Transfer and Bispectra for Decaying Turbulence with Passive Scalars: Velocity and Scalar Bispectra. In *Preprints, Twelfth Symposium on Turbulence, 24–26 Sept., 1990* Rolla, Missouri, (X.B. Reed, Ed.). University of Missouri, Rolla, A33-1.

———, R.M. KERR, and R. ROTUNNO, 1990: Potential vorticity in isotropic turbulence. *Proc. Conference of American Physical Society, Division of Fluid Dynamics*, 18–20 November 1990, Ithaca, New York. American Physical Society, 2268.

HEYMSFIELD, A.J., L.M. MILOSHEVICH, and *A. SLINGO, 1990: An observational and theoretical study of highly supercooled altocumulus. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 184–188.

JOHNSON, D.B., and R.M. RASMUSSEN, 1990: On the transition between wet-growth and dry-growth for graupel and hail. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 278–281.

*JOHNSON, R.H., S. CHEN, *G.J. STUMPF, and *D.L. BARTELS, 1990: The vertical structure of a midtropospheric vortex within the stratiform region of a mesoscale convective system. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 216–217.

KERR, R.M., and J.R. HERRING, 1990: Evolution of potential vorticity in turbulence simulations. *Proc. Conference of American Physical Society, Division of Fluid Dynamics*, 18–20 November 1990, Ithaca, New York. American Physical Society, 2306.

———, ———, and R. ROTUNNO, 1990: Inviscid simulations of turbulence. *Proc. Conference of American Physical Society, Division of Fluid Dynamics*, 18–20 November 1989, Ithaca, New York. American Physics Society, Woodbury, New York, 2268.

KLEMP, J.B., *M.J. McIRWIN, and W.S. BOYD, 1990: PolyPaint — A three-dimensional rendering package. In *Proc. Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, 5–9 February 1990, Anaheim, Calif. AMS, Boston, Mass., 286–293.

———, R. ROTUNNO, and W.C. SKAMAROCK, 1990: On the dynamics of gravity currents in a channel. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 166–167.

———, and W.C. SKAMAROCK, 1990: Adaptive-grid modeling of mesoscale processes. In *Abstracts, Joint*

United States–Peoples Republic of China Workshop on Mesoscale Meteorology, 19–21 September 1990, Boulder, Colo. NSF and NOAA, 40–43.

KNIGHT, C.A., and L.J. MILLER, 1990: First 5-cm radar echoes at low dBZ values in convective clouds. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 716–721.

KUO, Y.-H., and S. CHEN, 1990: Four-dimensional data assimilations of TAMEX special observations. In *Proc. Workshop on TAMEX Scientific Results*, 24–26 September 1990, Boulder, Colo. NSF, National Science Council of Taiwan, and NCAR, 115–120.

______, and S. LOW-NAM, 1990: On the predictability of explosive cyclogenesis. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 30–31.

LAWSON, P., 1990: Thermodynamic analysis of buoyancy and entrainment in cumuli using measurements from a radiometric thermometer. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 685–692.

LeMONE, M.A., and *J. JENSEN, 1990: Some aspects of the structure and dynamics of Hawaiian cloud bands. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 744–749.

______, and *D.P. JORGENSON, 1990: Momentum generation and redistribution in a TAMEX convective band. In *Proc. Workshop on TAMEX Scientific Results*, 24–26 September 1990, Boulder, Colo. NSF, National Science Council of Taiwan, and NCAR, 42–47.

______, J.C. FANKHAUSER, and *T. MATEJKA, 1990: Momentum generation and redistribution in convective bands: What have we learned? In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 198–199.

LENSHOW, D.H., 1990: Factors affecting the structure and stability of boundary-layer clouds. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 37–42.

______, and L. KRISTENSEN, 1990: Errors in measuring second-, third-, and fourth-order moments of turbulence variables. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, 30 April–3 May 1990, Roskilde, Denmark. AMS, Boston, Mass., 90–93.

*MARGOLIN, L.G., and P.K. SMOLARKIEWICZ, 1990. *Antidiffusive velocities for multipass donor cell advection.* Report UCID–21866, Lawrence Livermore National Laboratory, 44 pp.

*MATEJKA, T., and M.A. LeMONE, 1990: The generation and redistribution of momentum in a squall line. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 196–197.

MOENG, C.-H., and J. CURRY, 1990: The sensitivity of large-eddy simulations of a stratus-topped boundary layer to cloud microphysics. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 115–121.

______, and *U. SCHUMANN, 1990: Composite updraft and downdraft in stratus-topped boundary layer. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, 30 April–3 May 1990, Roskilde, Denmark. AMS, Boston, Mass., 7–10.

MONCRIEFF, M.W., 1990: Influence of atmospheric deep convection on boundary layer and surface processes. In *Proc. International TOGA Scientific Conference*, 16–20 July 1990, Honolulu, Hawaii. AMS, Boston, Mass., 145–152.

______, 1990: Momentum transport by organized convection. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 200–201.

MOORE, J., 1990: *Summary project report: Demonstration and evaluation of a wind shear and gust front detection and warning system in 1989 using the terminal NEXRAD (Raytheon NEXRAD prototype) radar and operational low-level wind shear alert system at Stapleton International Airport.* RAP NCAR, under FAA MOU PTFA-1-90-2-00049, 35 pp.

PALUCH, I.R., and D.H. LENSCHOW, 1990: Cloud structure and turbulent transports in the cloud-capped marine boundary layer, 1990: In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 153–158.

*PUESCHEL, R.F., *G.V. FERRY, *K.G. SNETSINGER, *J.K. GOODMAN, J.E. DYE, and D. BAUMGARDNER, 1990: Type I polar stratospheric cloud particles: Formation, properties, optical effects. Fall Meeting, American Geophysical Union, San Francisco, Calif., 3–7 December, 1990. *EOS Abstracts* 71, 43, 1246–1247.

*RANDALL, D.A., *Q. SHAO, and C.-H. MOENG, 1990: A physically based fractional cloudiness parameterization. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 178–182.

RASMUSSEN, R., A. CROOK, *C. KESSINGER, 1990: Precipitation bands in Colorado front range snowstorms: 15 November 1987 case study. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 63–64.

ROBERTS, W.F., *M.R. BAILEY, and *I. SHEA, 1990: Implementation of SWORD: Technology and experience. In *Proc. Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, 5–9 February 1990, Anaheim, Calif. AMS, Boston, Mass., 321–328.

______, *W.R. MONIGER, *B.deLORENZISL, *E. ELLISON, *J. FLUECK, *J.C. McLEOD, *C. LUSK, *P.D. LAMPRU, *R. SHAW, *T.R. STEWART, *J. WEAVER, *K.C. YOUNG, *S. RUBRICK, 1990: Shootout 89: A comparative evaluation of AI systems for convective storm forecasting. In *Proc. Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, 5–9 February 1990, Anaheim, Calif. AMS, Boston, Mass., 167–172.

ROTUNNO, R., and *D. KEYSER, 1990: On the formation of potential-vorticity anomalies in upper-level jet-front systems. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 82–83.

*SASSEN, K., A.J. HEYMSFIELD, and *D.O'C. STARR, 1990: Is there a cirrus small particle radiative anomaly? In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., J91–J95.

*SCHUMANN, U., and C.-H. MOENG, 1990: Top-hat profile approximations for vertical fluxes in the clear and stratus-topped convective boundary layer evaluated from large-eddy simulations. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, 30 April–3 May 1990, Roskilde, Denmark. AMS, Boston, Mass., 31–34.

SMOLARKIEWICZ, P., 1990: Orographic clouds in a low Froude number flow regime. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 743.

______, and R. ROTUNNO, 1990: Low Froude number flow reversal upwind of a three-dimensional obstacle. In *Preprint Vol., Fifth Conference on Mountain Meteorology*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 8.

*STAGE, S.A., *P. WELSH, and C.-H. MOENG, 1990: Mixing rate analysis of the stratocumulus-topped marine atmospheric boundary layer. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 107–114.

STOSSMEISTER, G.J., and G.M. BARNES, 1990: Initiation of a tropical cyclone vortex. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 26–27.

SZOKE, E.J., and *J.A. AUGUSTINE, 1990: An examination of the mean flow and thermodynamic characteristics of a mesoscale flow feature: The Denver cyclone. In *Preprint Vol., Fifth Conference on Mountain Meteorology*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., J-17–J-18.

TAYLOR, P.A., and J.C. WYNGAARD (Organizers), 1990: Planetary Boundary Layer Model Evaluation Workshop. Joint Planning Staff for WCRP, WMO, Geneva, 46 pp.

TRIER, S.B., 1990: Taiwan Area Mesoscale Experiment: A Guide to precipitation patterns during the 1987 field phase. NCAR Technical Note, NCAR/TN-350+STR, 333 pp.

______, and D.B. PARSONS, 1990: Numerical simulation of a prefrontal squall line observed during TAMEX IOP 8. In *Proc. Workshop on TAMEX Scientific Results*, 24–26 September 1990, Boulder, Colo. NSF, National Science Council of Taiwan, and NCAR, 62–67.

______, and ______, 1990: Numerical simulation of a subtropical prefrontal squall line. In *Extended Abstracts, Fourth Conference on Mesoscale Processes*, 25–29 June 1990, Boulder, Colo. AMS, Boston, Mass., 180–181.

*TZIVION, S., *T. REISIN, *Z. LEVIN, and G. FEINGOLD, 1990: Numerical simulation of cloud seeding with hygroscopic nuclei. In *Preprint Vol., Conference on Cloud Physics*, 23–27 July 1990, San Francisco, Calif. AMS, Boston, Mass., 693–697.

WANG, W., and Y.-H. KUO, 1990: On the formulation of a southwest vortex. In *Proc. Workshop on TAMEX Scientific Results*, 24–26 September 1990, Boulder, Colo. NSF, National Science Council of Taiwan, and NCAR, 182–185.

WEIL, J.C., 1990: Dispersion limits in the convective surface layer. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, 30 April–3 May 1990, Roskilde, Denmark. AMS, Boston, Mass., 344–347.

______, 1989: Recent developments in applied dispersion modeling. In *Proc. Environmental Research: 1989 Technology Transfer Conference*, Vol. 1, 20–21 November 1989, Ontario, Canada. Environment Ontario, Ontario, Canada, 20–26.

______, *R.I. SYKES, and *A. VENKATRAM, 1990: *Evaluating air quality models: Status and outlook*. Report prepared for the U.S. Environmental Protection Agency by the AMS/EPA Steering Committee on Air Quality Modeling, EPA, Washington, D.C., 54 pp.

* An asterisk denotes a non-NCAR author.

Research Applications Program

The Research Applications Program (RAP) became an NCAR-wide program reporting to the NCAR director on 1 October 1989. As a technology transfer unit for NCAR-developed technology, RAP conducts basic and applied research and develops technical "products" for national users of the aviation weather system in close collaboration with other NCAR divisions, most notably with the Mesoscale and Microscale Meteorology (MMM) Division, the Atmospheric Technology Division (ATD), and the Scientific Computing Division (SCD). RAP plays a key role in the Federal Aviation Administration's (FAA) Terminal Doppler Weather Radar (TDWR) and Low Level Wind Shear Alert System (LLWAS) programs to detect and warn of severe wind shear and other weather hazards in the airport terminal area. RAP is also participating with NCAR divisions, universities, and outside agencies in an aircraft icing initiative and a winter storms research project to improve our understanding of winter storm structure and dynamics and to improve icing forecasts. In addition, RAP is helping the FAA develop an improved aviation weather system for the United States.

Significant Accomplishments

- The first field season for the Winter Icing and Storms Project (WISP) was very active, with ten winter storms observed and much data gathered that will be used to analyze supercooled liquid water production.

- RAP refined the wind shear detection system for the FAA during the TDWR operational demonstration at Stapleton International Airport, Denver, Colorado. The integration of Doppler weather radar data with data from the Runway Extension LLWAS was demonstrated successfully.

- During the TDWR demonstration, real-time operational experiments were conducted to provide 30-min forecasts of thunderstorm initiation and advection in the Colorado Front Range. These forecasts were delivered to FAA facilities. In addition, a nonoperational, real-time tornado forecast/nowcast experiment was conducted for nonsupercell tornadoes.

- A three-year effort to develop an Advanced Aviation Weather System concept was successfully concluded. This new initiative will further mesoscale research, development, and technology transfer to provide improved short-term detection and warning of hazardous weather; it includes the creation of the Aviation Weather Development Laboratory, which will evolve from the RAP operations center. The program will commence in fiscal year (FY) 91.

- RAP continued to develop interdivisional relationships. There were seven joint appointments with MMM, including one long-term visitor. G. Brant Foote is on a two-year leave from MMM to head RAP's Applied Science Group. RAP also had three joint appointments with ATD.

Icing and Winter Storms

WISP

A major effort within RAP this year was planning and conducting WISP, a cooperative research effort designed to study the structure and evolution of winter storms. The primary goals of WISP are to improve our understanding of the processes involved in the production and depletion of supercooled liquid water in winter storms, and to improve the forecasts of aircraft icing in winter storms.

The first goal reflects the basic research component of WISP, designed to attract the participation of scientists interested in the basic processes of supercooled liquid water production and depletion. The second goal reflects the more applied research objectives of the FAA-sponsored Aircraft Icing Program. An important component of the Icing Program is the involvement of NOAA Forecast Systems Laboratory (FSL) and Wave Propagation Laboratory (WPL) in conducting a forecasting exercise and evaluation of remote sensors such as radiometers for supercooled liquid water. Roy Rasmussen is the project manager within RAP for the basic research aspects of WISP, and Marcia Politovich is the project manager within RAP for the Aircraft Icing Program. The 1990 field program was largely an NCAR project, with support from NOAA and the University of North Dakota. Key NCAR scientists involved were Rasmussen, Politovich, Wayne Sand, Charles Chappell, Cathy Kessinger, Kimberly Elmore, and Rita Roberts from RAP, and William A. Cooper and Mitchell Moncrieff from MMM.

Facilities used during the first field season included the NCAR CP-3 and Mile High radars, the University of Wyoming King Air aircraft, the University of North Dakota Citation aircraft, four cross-chain Loran atmospheric sounding system (CLASS) sites, 19 portable automated mesonet (PAM) stations, three radiometers, three wind profilers, and two radio acoustic sounding system (RASS) instruments. The radiometers, wind profilers, and RASS instruments were maintained by NOAA. The experiment was conducted from 1 February to 31 March 1990, during which ten winter storms were studied.

Significant findings from the first field season were: (1) supercooled liquid water (SLW) occurred predominantly during the occurrence of shallow, anticyclonic upslope storms; (2) highest values of SLW were located near cloud top; (3) SLW was located in regions of radar reflectivity less than 15 dBZ_e; (4) large drops were present near cloud tops of anticyclonic storms when strong vertical wind shear existed there; and (5) the spatial and temporal distribution of SLW varied significantly over the Front Range during winter storms. Rasmussen, Politovich, Elmore, and Kessinger are involved in detailed ongoing case studies using both the extensive WISP-90 observations and numerical model simulations to understand better the physical processes involved in the production and depletion of SLW.

SLW in the WISP Valentine's Day Storm

A number of anticyclonic, upslope storms occurred during WISP-90. They were characterized by relatively warm cloud-top temperatures (–15 to –10°C) and significant amounts of SLW (up to 0.7 g/m^3). A particularly long-lived storm occurred during the period 13–15 February 1990. This storm produced sustained periods of liquid water during the first two days and snowbands the last day. Rasmussen, Masataka Murakami (visitor from the Meteorological Research Institute, Ibaraki, Japan), Elmore, and Gregory Stossmeister are conducting a detailed case study of this storm with the goal of understanding the production and depletion of supercooled liquid water in such systems. The data employed in the study came from the CP-3 and Mile High radars, the University of Wyoming King Air aircraft, NOAA radiometers, surface mesonet stations (PAM and Program for Regional Observing and Forecasting Services [PROFS]), CLASS sounding systems, wind profilers, National Weather Service (NWS) soundings, and satellites. These data show that a shallow upslope cloud formed over the Colorado Front Range seven hours after the passage of a cold front from the north. This cloud contained column-integrated SLW above 0.2 mm for the next 30 h, as measured by three radiometers located along the Front Range. During this high-SLW period, two aircraft flights were conducted. The analysis to date has concentrated on the time period of the first aircraft flight, between 1711 and 1900 UTC, during which conditions were nearly steady. Radar reflectivities during this time were mostly less than 20 dBZ_e.

The flight data showed that most of the SLW was concentrated near the top of the stratiform cloud, and that low concentrations of dendritic ice crystals were present in the mid- to lower portions of the cloud in the northern portion of the domain (near Greeley), but not in the southern portion (along the slopes of the Palmer Divide). Rather, in this southern region low concentrations of large drops (up to 200 µm) were found to exist near the cloud top. Characteristic of both regions was strong vertical wind shear, which has been shown by Cooper to result often in the production of large drops if a turbulent mixing process occurs near cloud top. The main difference between the two regions was the cloud-top temperature. The region near Greeley had a cloud-top temperature near –15°C, while the region to the south had a cloud-top temperature of only −11.5°C. This suggests that a strongly temperature-dependent nucleation process may have existed in these clouds.

The radiometer data also revealed that the supercooled liquid water was not spatially uniform. Measurements from the three radiometer sites varied by factors of three to four from each other during this period. In order to investigate both the microphysical variations and the spatial variation of SLW, three-dimensional numerical simulations were performed by Rasmussen and Murakami using Terry Clark's (MMM) anelastic model. Two different microphysical parameterizations were used, the Koenig and Murray scheme and the Murakami scheme. Model results showed the SLW organized into bands oriented northwest to southeast, with a 50-km spacing. Higher values of SLW were also found in a north-south line up against the foothills. These results were in general agreement with the aircraft and radiometer data on SLW and showed the important role of the Front Range topography in forcing updrafts, and consequently SLW, in these anticyclonic storms. Future work will include further analysis of the microphysical variations from the northern to the southern portion of the domain and consideration of other time periods of the storm.

Precipitation Bands in Colorado Front Range Snowstorms

Prior to WISP-90, RAP scientists conducted a study of the 15 November 1987 snowstorm in which Continental Airlines flight 1713 crashed during takeoff. Rasmussen, Kessinger, and Andrew Crook have been investigating the structure, dynamics, and microphysics of this storm, including the origin of the heavy precipitation at Stapleton Airport just prior to the takeoff of Flight 1713.

This storm followed the typical synoptic evolution of major snowstorm events occurring in the Colorado Front Range (termed the Eastern Pacific Developmental Trough pattern by Tollerud and Howard). Three distinct precipitation periods were identified, a convective rain period at 0000–0900 UTC on 15 November, a propagating band period at 0900–1800 UTC on 15 November, and a stationary band period between 1800 UTC on 15 November and 0000 UTC on 16 November. Most of the work has focused on the latter two periods. During the period of snowband formation (0900–2300 UTC on 15 November), the 500-mb low was located over southwestern Colorado and the surface low over southeastern Colorado. The first cold front associated with this storm passed over Stapleton at 0200 UTC on 15 November with little or no precipitation, weak wind shifts, and small temperature drops. A second, shallow cold front passed over Stapleton at 1030 UTC. This secondary cold front was associated with a 5°C temperature drop, strong northerly winds (up to 25 m/s), and snow.

The propagation speed of the cold front was approximately 14 m/s towards the south. As this cold front passed over the Palmer Divide, snow bands were observed to form between 3 and 5 km above mean sea level (MSL), as determined by CP-2 radar. These bands were oriented southwest to northeast and moved to the northwest at 7 m/s. Spacing between bands varied from 15 to 30 km.

Analysis of wind profiler data from Flagler, Colorado, shows that the wind in the cloud layer (3–5 km) was southeasterly between 5 and 10 m/s, suggesting that the bands were propagating with the mean flow at their level. The Doppler data from the CP-2 radar and the Stapleton profiler show that the strong northerly flow associated with the secondary cold front was relatively shallow initially, extending to 1 km above ground level (AGL) at 0900 UTC, increasing, however, to 2 km AGL by the time of the aircraft crash at 2115 UTC.

A number of mechanisms for band formation were considered in this case, including: (1) topographic forcing as the cold front propagated over the Palmer Divide, (2) bands forced by cold fronts and density currents, (3) conditional symmetric instability (CSI), and (4) convective bands. Conditional Symmetric Instability was eliminated because the bands were aligned perpendicularly to the thermal wind, while CSI theory predicts bands parallel to the thermal wind. It was decided to study the forcing of precipitation bands by a cold front using the Clark anelastic, nonhydrostatic mesoscale model. This model includes explicit ice physics with two categories of ice: pristine ice and graupel. The model was configured with one nested domain. The outer domain had horizontal grid spacing of 6 km and vertical grid spacing of 400 m. The inner model had horizontal grid spacing of 2 km and vertical grid spacing of 400 m. The outer model was positioned to cover most of the Front Range region of Colorado, while the inner model was positioned over the Palmer Divide. The cold front was simulated as a density current. The inflow wind profile at the northern boundary was specified to have a hyperbolic tangent profile, which was adjusted to preserve mass continuity at the boundary. The depth of the inflow was specified to be 1 km and the temperature deficit to be 5°C, based on the observations. The velocity of inflow was determined from Benjamin's density-current equation to be 15 m/s, in good agreement with the observed propagation speed of the cold front of 14 m/s. The model was initialized with a single prefrontal sounding obtained from a combination of the Stapleton six-channel radiometer thermodynamic data at 1000 UTC and the 1200 UTC Flagler wind profiler data. These times were chosen to represent conditions just prior to the secondary cold front passage. The composite sounding was stable throughout the layer, with strongest stability below 700 mb and nearly moist adiabatic from 700 to 500 mb. The base state winds were specified to be southeasterly throughout the depth of the model.

The model was run sufficiently long to allow the cold front to propagate through the domain. As the cold front propagated down the Front Range, precipitation bands formed with a spacing of approximately 50 km. In contrast to the observed bands, the simulated bands propagated to the south at a speed of 15 to 16 m/s (in other words, with approximately the same speed and direction as the cold front). Furthermore, the simulations indicated no preferential development over the Palmer Divide. The bands in this first simulation formed in the crests of an internal gravity wave, which was forced by the leading edge of the cold front and which propagated in the stable stratification above the front.

These model results suggested that there may have been a layer of conditional instability in the prefrontal atmosphere. Indeed, the 00 UTC Denver sounding on 15 November showed the presence of convective instability between 750 and 500 mb just nine hours prior to the formation of the bands. In addition, thermodynamic soundings from the six-channel radiometer often tend to smooth low-level inversions. These observations suggested that the base state be destablizied slightly around 700 mb. This was achieved by increasing the temperature at 700 mb by 1°C and enhancing the moisture below 700 mb to 90% of saturation. In this second simulation, precipitation bands formed with a 15–20 km spacing and propagated towards the northwest at 8–10 m/s, in good agreement with the observations. Since the bands result from an instability in the flow, they tend to move with the mean wind at the level of instability, which was approximately 8–10 m/s towards the northwest. Furthermore, since the instability is forced by the leading edge of the front, the bands tend to form parallel to that edge.

The above results suggest that snowband formation in winter storms can often be very sensitive to the thermodynamic structure of the atmosphere. Better forecasts of these types of conditions may require both the use of high-resolution models, such as the Clark model which can resolve snowbands on the 20-km scale, and the availability of high-resolution observations of the atmospheric state in which the bands develop.

Icing Forecasts Using LAPS

Politovich and Paul Lawson (long-term visitor with RAP, MMM, and FSL, from SPEC, Inc.) have been collaborating with Steve Albers (FSL) in the development of applications algorithms for use with the FSL Local Analysis and Prediction System (LAPS). FSL has developed LAPS with 10-km horizontal and 50-mb vertical resolution, covering most of Colorado. LAPS incorporates a variety of data that will soon be operationally available, including surface station and upper-level reports, NOAA wind profilers, pilot reports (including automated reports), NEXRAD radars, and Geostationary Operational Environmental Satellite (GOES) satellite data. LAPS provides three-dimensional analyses of thermodynamic, wind, and cloud fields on an hourly basis. Horizontal or vertical slices through the domain may be chosen for display.

Two schemes are being developed to calculate SLW within the LAPS domain. The first is a revised Smith-Feddes algorithm, which uses a single sounding of the atmosphere combined with human input of relevant parameters to determine the SLW content at discrete levels. The original algorithm was developed in 1974 and since has been revised and improved in many ways.

There are several drawbacks to this approach to forecasting aircraft icing. One involves the representativeness of a single sounding. The NWS's upper-air network launches sounding balloons every 12 h at approximately 200 n mi spacing over the continental United States. Weather conditions can change considerably at any given location over a 12-h period and can also vary significantly over these spatial scales.

Another problem with the original Smith-Feddes method is the amount of human input needed in determining cloud base and top heights, the existence of multiple layers, and the cloud type. To circumvent these problems, the Smith-Feddes calculation was incorporated into the LAPS system. The vertical profile over each horizontal grid point was treated as a separate sounding, and the Smith-Feddes algorithm was applied to that sounding. The SLW field was then obtained for each grid point, based on the temperature within the grid and the three-dimensional nephanalysis. The cloud type was assumed to be stratus for this exercise.

The other scheme used the cloud-top temperature to adjust the SLW from the value obtained by lifting a parcel from the base of the cloud. This was meant to account crudely for the depletion of SLW due to ice crystals. At each horizontal grid point, the cloud base was found, and an air parcel was simulated to rise adiabatically from the base to cloud top. The adiabatic SLW content was calculated at 50-mb intervals and then reduced by a factor depending on the cloud-top temperature.

NEXRAD radar is one of the data sources ingested by LAPS and provides a direct measure of the precipitation falling within those parts of the domain under surveillance. A comparison of radar reflectivity with the liquid water content measured from the aircraft revealed a threshold near 10 dBZ_e, above which no liquid water was detected. This suggested a more direct method of adjusting calculated SLW to account for depletion by ice or, more correctly, precipitation.

An estimate of droplet median-volume diameter (MVD), based upon cloud type, was also implemented within the LAPS domain. Whereas in the Smith-Feddes algorithm cloud type was specified as stratocumulus for the purpose of the calculation, for computing MVD the cloud type determination was made using stability and temperature. Stability was determined using the temperature lapse rate.

An important part of the development of these algorithms has been the comparison of LAPS-derived values with measurements from research aircraft. Data from flights that took place during WISP-90 have been used to verify the methods used to derive liquid water and droplet size, and as a check on temperature analysis within LAPS. Improvements to LAPS based on the information gained by these comparisons are constantly being made to the software package.

Development of an Icing Severity Index

It is difficult to assess the severity of icing conditions even when pilot reports of icing are available. The current icing severity index of trace/light/moderate/severe is subjectively based on the pilot's concept of his or her airplane's ability to deal with icing and is not uniquely related to cloud conditions.

Politovich and Sand are leading a portion of the FAA's Icing Program designed to improve this situation. The primary task of this comprehensive program is to develop improved icing forecast methods as well as to devise a new icing severity index. This index should be meteorologically based, consider aircraft performance changes caused by ice accretion, and have meaning to the pilot. The most important meteorological factors in icing severity are temperature, SLW content, and droplet size. Other factors such as airspeed, airfoil shape, and the efficiency of anti- or de-icing equipment are aircraft-specific and as such will not be explicitly included as part of a new icing index system.

A new ten-level index is under development, with severity increasing with index number. Category 10 is reserved for freezing rain and drizzle and large supercooled cloud droplets with diameters greater than about 50 microns. Index values are assigned to combinations of SLW, temperature, and droplet size. An assessment of cloud type is used to characterize the continuous or intermittent nature of the icing environment. Initial tests of this concept will be conducted as part of WISP-91.

National Icing Forecast Evaluation

The National Aviation Weather Advisory Unit (NAWAU) has developed forecasting guidelines based upon model products issued by the National Meteorological Center (NMC). Their methods use NMC national-scale model forecast fields to identify temperature, moisture, and vertical velocity fields conducive to aircraft icing.

The forecasts depict areas where icing is possible, given that clouds will form. Forecasts are prepared three times daily for three regions in the continental United States: eastern, central, and western. Altitude ranges are usually from the freezing level to a maximum designated by the forecaster. NWS soundings may be checked to find the –15°C level or cloud tops, either of which can be used as the upper limit to icing forecasts. Expected intensity is determined by examining current pilot reports near each forecast area.

Pilot reports from February and March 1990 were used by Jeff Cole and Politovich for an evaluation of NAWAU forecasts. Characteristics of the pilot reports were analyzed to aid in the interpretation of the forecast comparison. For each hour of each day during this period, a map of the pilot reports, coded by intensity level, was produced (a total of 1416 maps). The active icing forecast area for each region was then traced onto each map and "hits" and "misses" recorded.

The "miss ratio," the ratio of pilot reports outside active forecast regions to the total number of reports in that region, was used as the main evaluation parameter. Unfortunately, the lack of null icing reports made it impossible to assess statistically the overforecast of regions. However, overforecasting was addressed by a case study approach, through which the meteorological influences on icing were evaluated.

For February and March combined, the overall miss ratio was 26%. The eastern, central, and western regions had individual miss ratios of 26%, 29%, and 21%, respectively. The miss ratio was higher when fewer reports were received, which may imply that these were more marginal icing events and thus more difficult to forecast. At about 200 reports per day, the miss ratio settled to below 40%. There was little relation between severity level and the miss ratio for any region; however, the miss ratio was usually lower for the severe category. The miss ratio remained fairly steady during the daytime but varied at night when fewer reports were received. There was a slight tendency for the miss ratio to increase with time after issue, which was strongest for the western region.

To summarize the findings of this study:

- There is considerable variation in forecast skill. This may be the result of having many individuals involved in forecast preparation using various tools and methods. For example, some forecasters do not examine soundings or use thickness forecasts to determine cold-side limits for icing, while others do.

- More significant icing is missed less often.

- Miss ratios increase with time from issue.

- Orographic influences are important. Pilot reports are concentrated over mountainous areas such as the Pacific coastal ranges, the western mountains, the Rockies, and the Appalachians. Icing tends to be reported from these areas when the relative humidity is high (based on NWS upper-air reports) at 850 or 700 mb; thus, it may be missed by considering only the boundary layer.

- Icing forecasts tend to extend too far into the north, and too high, where conditions are likely to be too cold for formation of significant icing.

- An automated forecast and display system is desirable. This would provide consistency in forecasts and allow for improvements to be made in the actual forecast methods. It would also free up more of the forecasters' time to concentrate on mesoscale and local effects and other special weather situations.

Hourly Snowfall Nowcasting

The efficiency of managing airport operations and airport traffic during snowfall, including the de-icing of aircraft, can be improved by reliable nowcasts of hourly snowfall. A nowcasting experiment is being conducted as part of WISP to develop and test such a capability. Nowcasts of hourly snowfall amounts are made for Denver Stapleton Airport.

Three nowcasting tools have been developed, which are used in concert to prepare the nowcasts. Reflectivity output of the Mile High Doppler radar has been calibrated in terms of snowfall intensity by applying Z-S relationships used by FSL scientists during area snowfalls of the past two years. Software has been developed in RAP to track the motion of the heavier snow areas and to extrapolate their future position.

Secondly, during an exploratory nowcasting effort last year, Chappell determined that the infrared satellite imagery was quite useful in tracking mesoscale features embedded in upslope or cyclonic storm cloud systems. Specifically, a color table that gave good resolution to cloud-top temperatures in the range from –8 to –25°C was used to monitor and anticipate changes in snowfall intensity. Temperatures at the colder end of this range usually signaled a deeper cloud with enhanced crystal concentrations, both of which act to increase snowfall intensity.

Finally, a diagnostic algorithm was developed by Chappell that provides an estimate of snowfall rate. This algorithm is a crude snowfall parameterization that gives a steady-state solution for the snowfall rate after certain microphysical processes have been allowed to operate. The algorithm has been merged with LAPS, which provides the necessary input to the algorithm: a description of cloud distribution in space, temperature and moisture fields, horizontal winds, and estimates of the vertical motion.

Snowfall rate depends upon satisfactory estimates of crystal concentrations, masses, and fall speeds. Ice crystal concentrations are considered to vary with cloud-top temperature according to a mean spectrum observed for the region. The algorithm computes the rates of ice growth and condensate production at each grid-point column within the LAPS domain. The steady-state snowfall rate is computed from the rate of ice growth summed over the vertical extent of the cloud. The rate of ice growth is constrained not to exceed the rate of condensate production in a grid volume.

Accretional ice growth is crudely accounted for by considering it to be a function of the ratio of the diffusional growth rate of ice to the rate of condensate production in the cloud. If the rate of ice growth by vapor diffusion equals or exceeds the rate of condensate production, the rate of ice growth by accretion is assumed to be zero, since cloud water is being depleted by the diffusional growth of ice and is not available for the riming process. If the rate of condensate production exceeds the rate of ice growth by vapor diffusion, there is a net accumulation of cloud water, and riming contributes to crystal growth. The parameterization gives a small increase in accretional growth as the rate of condensate production begins to exceed the rate of diffusional ice growth. Estimates of crystal fall speed and LAPS-derived vertical velocity are used to define the actual fall speed relative to the ground. The snowfall rate is then equal to the vertical flux of ice crystals reaching the surface.

Preliminary testing of the snowfall algorithm began with its application to portions of four winter storms that occurred on 15 and 28 February 1990 and 6 and 24 March 1990, using output from the LAPS analysis for several hours during each storm. The output from the algorithm was compared to hourly snowfall amounts measured by volunteer observers in the area to obtain an initial evaluation of the algorithm and to provide guidance for improving it prior to its application as a nowcasting tool during WISP-91.

Real-Time Dual-Doppler Analysis for Use during Field Operations

The computation of synthesized dual-Doppler radar wind fields was first accomplished in real time during field operations of WISP in March 1990 under the guidance of Kessinger and Wen Chau Lee (ATD). Data collected from the Mile High and the NCAR CP-3 radars located near Denver were transported via T1 lines to the RAP operations center in Boulder. The reflectivity and radial velocity data in spherical coordinates from each radar were simultaneously interpolated into Cartesian space on an Alliant computer. The radar data were linearly interpolated by a fast algorithm implemented by Jon Lutz, Robert Barron, and Michael Carpenter. The Cartesian grid had (X,Y,Z) dimensions of 256 x 256 x 32 with grid spacings of 0.75 x 0.75 x 0.29 km. A clutter map was used to eliminate large terrain targets. Once the interpolation phase was completed, the Cartesian volume was transmitted to an Ardent computer for display and computation of the horizontal wind components. The horizontal wind components were computed within a partial area of the total domain available, as determined by the radar geometry. Integration for vertical motion was not performed. The horizontal winds were calculated and displayed about 5 min after a volume scan was completed. Selected volumes were saved for evaluation purposes.

Results from the real-time calculation were compared with methods traditionally used in postanalysis. Preliminary results indicated that the real-time, dual-Doppler analysis technique produced wind and reflectivity fields comparable to those of postanalysis methods. The real-time fields were noisier, especially in low signal areas, but in areas with strong radar return, the wind fields were in qualitative agreement.

Thunderstorm Weather

The CINDE Case Study of 17 July 1987

Utilizing data from 17 July 1987 that were collected during the Convection Initiation and Downburst Experiment (CINDE), James Wilson, Foote, Crook, James Fankhauser (MMM), Charles Wade, John Tuttle, Cynthia Mueller, and Steven Krueger (University of Utah) completed a paper that demonstrated the role of boundary-layer convergence zones and horizontal convective rolls in the initiation of thunderstorms. Utilizing Doppler radar, aircraft, mesonet, balloon sounding, profiler, and photographic data and the Clark numerical model, the initiation of thunderstorms along a preexisting boundary-layer convergence line was studied. Both the observations and model results indicated the storms were triggered at the intersection of the convergence line and horizontal rolls where enhanced updrafts were present. The critical factor governing time of storm development appeared to be related to a balance between horizontal vorticity in the opposing flows on either side of the convergence line. This result was similar to earlier theoretical studies by Richard Rotunno (MMM). The effect was to allow the updrafts in the convergence line to become more erect and the convergence zone deeper. The modeling results also indicated that storm initiation was very sensitive to the depth of the convergence line circulation. The initiation of individual storms cells frequently coincided with the location of misocyclones along the convergence line. Model results suggested this was because both events were caused by locally strong updrafts. The misocyclones resulted from stretching of existing vorticity associated with the convergence line. This was most likely to occur where a convective roll intersected the convergence line forming a local maximum in vorticity, convergence, and vertical motion.

Formation of Nonsupercell Tornadoes

Based on single-Doppler radar studies, it has been hypothesized that nonsupercell tornadoes develop when small vortices produced by shearing instabilities along a surface convergence boundary, as just discussed for the 17 July 1987 case, become stretched in the updrafts of developing thunderstorms and eventually intensify to tornadic strength. In an attempt to prove this hypothesis, Roberts and Wilson have been studying the formation of three nonsupercell tornadoes that occurred near Denver on 15 June 1988 within range of two Doppler radars. The parent storms formed above the collision of two surface outflows in an environment characterized by conditional instability, weak vertical wind shear, and minimal vertical vorticity, in contrast to supercell storm environments. Incipient F2–F3 intensity tornadoes were detected during the intensification stage of storm growth in the absence of any storm-scale rotation or mesocyclone, characteristic of nonsupercell tornadic storms. Analysis of horizontal vorticity vectors derived from the dual-Doppler wind field showed little correspondence with the horizontal wind field; streamwise vorticity patterns observed with nonsupercell tornadoes exhibited less coherence than those observed with supercell tornadoes.

The vertical vorticity and vertical velocity fields were examined to determine the mechanism of tornadogenesis. Vortices that formed along the collision of the surface outflows were observed to build in height and strengthen with time, coincident with storm growth overhead. The surface vortex and the core of maximum storm updraft became aligned vertically and intensified by the time of tornado touchdown. Plots of the divergence and tilting terms of the vertical vorticity equation for the layer from 0.2 to 2.2 km AGL indicated a continual increase in the magnitude of the divergence term in the 30-min period preceding touchdown of each tornado, in contrast to the tilting term that remained essentially constant and weakly positive during the same time period. The magnitude of the divergence term was approximately 4–6 times larger than the corresponding magnitude of the tilting term. Results of this study provide evidence that surface convergence played a dominant role in the intensification of the surface vortex, while tilting of horizontal vorticity in the vertical contributed minimally. Tornadogenesis ensued in this case from increased convergence and stretching of the surface vortex by an intensifying storm updraft directly overhead.

The Use of a Numerical Cloud Model in the Short-Term Prediction of Convection

A nonhydrostatic cloud model was used to provide guidance to nowcasters in the prediction of severe convection as part of the 1990 RAP summer program. In order to provide easy access and user friendliness, the model was run on a dedicated workstation in the RAP operations center. Because of the workstation speeds available in 1990, this meant that only limited-domain, two-dimensional simulations could be performed. (With the workstation speeds now available, three-dimensional simulations with 42 cubed domains can now be run several times faster than real time and are planned for the 1991 convective season.) Of course, the two-dimensional assumption limited the model's applicability; however, it was felt that there were still a number of quasi-two-dimensional forecasting problems to justify this approach.

The numerical model was configured primarily to examine the problem of storm formation at atmospheric boundaries. The model could be initialized with two types of boundaries: those with a significant temperature contrast (sometimes called density currents) and those with very little density contrast (called convergence lines). To ensure a correct mass/velocity balance for these boundaries, analytical solutions for steady-state flow were used as initial conditions. This meant that by measuring just two parameters (velocity difference and height of the mixed layer for convergence lines, and depth of the cold air and temperature difference for density currents) a complete solution could be found for the flow. The procedure for making a prediction was then to measure these parameters for any boundary in the observing network to obtain a representative sounding using a mobile CLASS system, and then to initialize the model with the sounding and the analytical solution of the boundary.

In practice, the two-dimensional model was probably most useful in giving the nowcasters insight into the form of convection that might develop under certain circumstances. Some null, model-based forecasts were issued that later were verified; however, this region of the prediction contingency table is both the largest and the least interesting. On a few occasions the model predicted no convection, while the radar screen alongside indicated several 40–60 dBZ_e echoes.

One particular example of model failure occurred on 6 July and has been examined in some detail. Late in the afternoon of 6 July a strong gust front moved south along the Front Range of the Rocky Mountains and collided with a stationary convergence line, producing several 50-dBZ_e cells. However, a sounding released very close to the collision point showed little conditional instability. The numerical model that used this sounding and was configured to simulate the collision of gust front and convergence line also produced no convection. One possible explanation for the failed forecast was inaccuracy in the sonde's moisture measurement. A second possible explanation was that there existed significant variability in boundary-layer moisture (with dewpoints varying by 1–2°C) and that the sonde sampled a relatively dry region. Sonde ascent rate and radar data indicated that the sonde ascended in a downdraft. Thus, the sonde probably sampled less moisture than the horizontal average in the region of the collision, which caused the model to fail in its forecast of convection.

Real-Time TREC

Tuttle has optimized the TREC (Tracking Radar Echoes by Correlation) software to run in near real time on a minicomputer for use during field operations. TREC is a single-radar technique that objectively identifies and tracks radar echo patterns to determine their translational motion, and hence the local wind. It involves the cross-correlation of echo features measured at two times a few minutes apart. Typically, the cross-correlation is done on arrays of data 5–10 km on a side with about 50% overlap between adjacent arrays. The array size determines the smallest scales resolved. Although TREC has been applied to storms, it has been shown by Tuttle and Foote to be best suited for applications to clear-air echoes where misleading results due to the evolution and sedimentation of hydrometeors in a shear flow are avoided.

During the 1990 summer field program conducted by RAP in northeastern Colorado, TREC was used to provide mesoscale wind information in the boundary layer using data from the Mile High Radar. During operations, data were transferred from the radar to an Ardent minicomputer through a high-speed link. TREC was applied to the lowest four or five elevation angles (where most of the clear-air echoes are concentrated) of the incoming polar coordinate data. The resulting vectors were interpolated to a Cartesian grid and displayed in the operations center. The typical time lag from data collection to vector display was about 10 min. Although TREC became operational only toward the end of the experiment, its utility was demonstrated by providing mesoscale wind information out to ranges of 60–70 km.

Microburst-Producing Virga Line

In collaboration with Roger Wakimoto and David Kingsmill (University of California, Los Angeles), Kessinger has been examining the 9 July 1987 microburst-producing virga line observed during CINDE. The virga line was characterized by low reflectivity ($\leq$ 35 dBZ_e) and produced five microbursts. This case was unique since dual-Doppler radar data, cloud photography, in situ aircraft data, soundings, and mesonet data were collected on the virga line. The dual-Doppler wind fields were superimposed on the cloud photographs using standard photogrammetric techniques to determine whether visual clues existed to warn approaching pilots of the microbursts' location. It was found that the downdrafts originated in areas where the virga was most dense, but advected from the origination point due to storm motion. Therefore, dense virga does not necessarily give a precise location of the downdraft location; rather, it indicates a general area to be avoided. The one-dimensional, detailed microphysical downdraft model of Srivastava was used to examine possible forcing mechanisms for the microbursts on this day. Preliminary results suggested that sublimation may have been the critical factor in the downdraft formation. A virga line that did not produce microbursts (a null event) happened earlier on the same day and will be examined to see how it differs from the microburst-producing virga line.

The 11 July 1988 Microburst at Stapleton

During the early afternoon of 11 July 1988 while the TDWR operational demonstration was underway, thunderstorms formed over the mountains west of Denver and moved eastward over the plains. By 1530 LT, several cells approached the Denver area. One of these, located immediately northwest of Stapleton, was among the more vigorous of several storms within the complex. It produced the most intense microburst investigated to date using dual-Doppler radar techniques, but the microburst was located several kilometers east and south of the main precipitation shaft. Four air carrier jet transports penetrated this microburst.

Using air parcel and hydrometeor trajectories derived from 14 dual-Doppler radar analyses spanning 35 min, Elmore and Politovich proposed the following scenario to explain the observed events: graupel particles that formed within the cell were lifted into a region of strong northwesterly winds near storm top, where the updraft was strongly sheared and the particles carried downwind. As the updraft weakened, the particles began to descend and were carried south and east of the main cell. Once these particles reached approximately 7 km MSL, they encountered a layer relatively unmodified by the convection containing strong westerly winds and a minimum equivalent potential temperature. The graupel particles then rapidly sublimed, causing localized cooling leading to the intense downdraft and microburst. Independent modeling work by Fred Proctor (NASA Langley Research Center) has supported this interpretation of events.

Denver Summer Nowcasting Evaluation

A considerable effort in RAP has gone into research leading to conceptual forecast models and to testing of these models during summer forecasting experiments. The models and forecasts are for place- and time-specific locations of radar reflectivity associated with storms. During the summers of 1989 and 1990, RAP meteorologists prepared 30-min forecasts that were displayed at the Stapleton Air Traffic Control (ATC) tower and Approach Control, and at the Center Weather Service Unit in Longmont.

The forecasting methodology is heavily dependent on detecting and monitoring the movement of Doppler radar-detected, clear-air boundary-layer convergence lines. Previous work by Wilson showed that there was a strong relationship between these radar-detected boundaries and storm initiation. However, the precise time and location of storm initiation was dependent on the local stability. Wilson and Mueller are currently studying the temporal and spatial variability of the boundary layer and the tools required to forecast the local stability. These studies use mesonet and sounding data collected during the CINDE experiment. The primary source of variation both spatially and temporally is the moisture field. Studies show that the correlations of the low-level mixing ratio (averaged over the lowest 50 mb) between soundings taken at 0500 vs. 1100 and 0500 vs. 1400 LT are 0.74 and 0.64. Spatial analyses show that there is an average deviation of 1 gm/kg of moisture in soundings that are taken within 30 min of each other over an 8000-sq-km area. Numerical model results indicate that variations of this magnitude affect whether storms can form and their subsequent strength. Soundings taken in proximity to the radar-detected boundaries are beneficial to forecasting convection.

Surface moisture as detected by well-calibrated mesonet stations may also be helpful in anticipating the local stability of a region. Mixing ratio and potential temperature data from mesonet and soundings (lowest 50 mb average), taken during the afternoon when the boundary layer is well mixed, have correlation coefficients of 0.95 and 0.83. In addition to the local stability, the vertical wind shear below cloud base relative to the boundary is shown to influence storm growth.

During the 1989 and 1990 forecast experiments, quality mesonet measurements of moisture were not available, and there were a limited number of special soundings. Thus the forecasters had to assess local stability by monitoring the cumulus cloud development. The forecasters were able to successfully include storm initiation and dissipation in their forecasts. Thus, they were able to outperform persistence and echo advection, as shown in the following table (spatial resolution is 25 sq km); POD is probability of detection, FAR is false alarm ratio, CSI is Critical Success Index.

	POD	FAR	CSI
Human	0.55	0.85	0.14
Advection	0.15	0.75	0.10
Persistence	0.11	0.84	0.07

An important element in the forecast procedure was the identification of existing cumulus clouds along and in the proximity of boundaries. Provided upper clouds do not obscure the cumulus clouds, satellite imagery could serve this purpose. However, typical time (30 min) and space resolution (5–30 km) errors in registering the data need to be improved. The forecasters had particular difficulty in forecasting the evolution of existing storms. Future observational and modeling studies need to focus on means to anticipate storm evolution based on mesonet and Doppler radar data.

Darwin Experiment

During February 1989 and March 1990, an experiment was conducted near Darwin, Australia (12° south latitude) on the nowcasting of tropical thunderstorms. The experiment included Wilson, Rod Potts and Tom Keenan (both of the Australian Bureau of Meteorology), and operational forecasters from Sydney and Darwin. The experiment was based on detection of boundary-layer convergence lines by Doppler radar. As previously demonstrated in the United States, "clear-air" Doppler signatures could be tracked and directly related to the location of thunderstorm generation and the occurrence of wind shifts.

The Doppler radar proved useful in detection of sea breeze fronts and storm outflow boundaries that initiated afternoon thunderstorms. During the evenings, squall lines that were generated several hundred kilometers to the east would occasionally pass through the area, producing spectacular lightning, heavy rain, and strong surface winds. The Darwin Weather Service issued public warnings of high winds and heavy rain based on the radar signatures. Playing an important role in producing strong surface winds was the presence of a strong rear-to-front wind maximum that originated in very dry air at about 3 km and that descended to the ground as a gust front. Downbursts were a common phenomenon that occurred in both the locally generated thunderstorms and large squall lines.

During periods of strong low-level flow from the ocean, boundary-layer "clear-air" radar return disappeared due to the absence of insects over the ocean. The implication for future tropical experiments over the ocean (like the Tropical Ocean and Global Atmosphere program's Coupled Ocean-Atmosphere Response Experiment) is that natural clear-air signals cannot be depended on to study the boundary layer.

TDWR

Research and development activities associated with the FAA's TDWR program continued this year. The NCAR Mile High Radar was shared between the FAA and NWS to support the community and aviation needs for the Colorado Front Range. A scanning strategy was developed that allowed the radar to partially emulate a NEXRAD and a TDWR. The major objective of the TDWR program this year was to demonstrate a wind shear warning system that combined data from the TDWR and the Stapleton Airport LLWAS. This combined system used the intelligence from both TDWR and LLWAS to provide a single alert for air traffic controllers. The TDWR/LLWAS Integration software was developed, tested, and demonstrated by RAP.

TDWR operations were conducted from 1 June to 7 September, lasting from 1200 to 1900 LT daily. Wind shear alerts from the integrated TDWR/LLWAS system and other TDWR weather products were provided to the Stapleton ATC tower and Approach Control, and the Air Route Traffic Control Center, Central Weather Service Unit (CWSU) in Longmont, Colorado. During operational periods, the TDWR system protected Stapleton Airport from the hazards of wind shear. The TDWR system was operated from the RAP operations center in Boulder. The operations center contains numerous computing facilities and displays that allow personnel not only to monitor the system but also to conduct scientific research on convective storm systems. Meteorologists, radar analysts, and technicians were stationed at the facility to monitor system functions.

During the 1990 TDWR Project, wind shear alerts were provided to the tower supervisors on geographic situation displays (GSDs), and the runways' approach and departure corridors' wind shear alerts were provided to the ATC tower controllers on alphanumeric Ribbon Display Terminals (RDTs). Both GSDs and RDTs were developed at RAP. The wind shear alert information on the RDTs was read directly to pilots approaching and departing Stapleton Airport. Other features displayed on the GSD included gust fronts, wind shift lines, precipitation, operational LLWAS winds, storm motion vectors, and 30-min convection initiation nowcasts.

The capability of the Runway Expansion (16-station) LLWAS was demonstrated at Stapleton Airport on 8 July 1989 when it detected a microburst at the north end of the airport on the approach end of runways 17 Left and Right. After being cleared by air traffic control for a visual approach, a pilot of a commercial flight heard three microburst alerts, the first a 60-knot loss in wind velocity. The pilot continued his approach until he heard the second alert, which indicated a 95-knot loss at three-mile final. He executed a missed approach at approximately 600 ft AGL at about the three-mile final, and the aircraft did not experience the microburst until about the 0.5-mile final at approximately 1000 ft AGL. The aircraft lost 50 knots air speed and 400 feet in altitude before safely exiting the event. The pilot believes that the microburst alert and immediate avoidance/go-around were instrumental in averting a much more serious outcome.

The TDWR/LLWAS Integration algorithm, developed in RAP, combines data from the LLWAS and TDWR in order to generate an integrated wind shear product that is both timely and more accurate than products provided from either stand-alone system. The TDWR/LLWAS Integration algorithm produces alerts for both microbursts and gust fronts. When aircraft fly through microbursts, they experience a loss in air speed; however, aircraft penetrating a gust front typically experience an air speed gain. The TDWR and LLWAS systems produce alarms that identify the shear type, location, and magnitude. The integration algorithm functions as follows.

The wind-shear-with-loss alarms come from microburst alarms generated by both TDWR and the wind-shear-with-loss alarms that are generated by the LLWAS. For those shear areas within the LLWAS network (within 2 n mi of Stapleton), the wind-shear-with-gain alarms come from the LLWAS runway-oriented, wind-shear-with-gain algorithm; however, for cases where the performance-gaining shears are located outside the LLWAS network, the alarms are generated by the TDWR gust front detection algorithm. Finally, an alarm-generating decision logic is applied to the wind-shear-with-loss and wind-shear-with-gain data in order to generate warnings that will indicate a worst-case magnitude and first-expected-encounter-location for each operational runway.

One of the most challenging product development efforts at RAP has been associated with developing a capability to predict the location, movement, and intensity of convective storms 30 min before initial storm development. For the past two years, RAP scientists have been developing, testing, and demonstrating a nowcast product that attempts this goal. Scientists monitor radar, thermodynamic, and kinematic parameters in real time to determine the location of storm development (storms must reach a radar reflectivity greater than 40 dBZ). Once a storm has been predicted, scientists enter the coordinates into a workstation for display at local FAA facilities. The controllers use this information as a strategic tool to vector aircraft around known or predicted storms. During the 1990 TDWR operations, a two-dimensional microphysical model was also used as a tool to predict storm growth. The model ingests environmental data and predicts storm development two hours ahead of real time. The operator can manipulate boundary conditions and environmental winds to reflect actual conditions.

Staff and Visitors

Staff

Director's Office

Lisa Chambers
Deborah Davis
Joanne Dunnebecke
Deborah Henson
Ellen Martinez
John McCarthy (director)
Wayne Sand (deputy director)
Art Shantz (associate director)

Demonstration Facility

Cleon Biter
Larry Cornman
O. Tres Hofmeister
William Mahoney (group head)
James Moore
Joan Tanous
Ren Tescher

Applied Science Group

Charles Chappell (long-term visitor)
Andrew Crook (50%)
Kimberly Elmore
G. Brant Foote (group head)
Cathy Kessinger
Jon Lutz
Carol Makowski
Masataka Murakami (joint long-term visitor with MMM)
Cynthia Mueller (38%)
Marcia Politovich (75%)
Roy Rasmussen (75%)
Rita Roberts
John Tuttle (50%)
Charles Wade (50%)
James Wilson (50%)

Engineering Systems Group

Robert Barron
Kent Goodrich (long-term visitor)
Richard Grubin
Frank Hage
Corrine Morse
William Myers
Sandra Yuter
Gerry Wiener (group head)

Computer Systems Group

David Albo
Gary Blackburn (75%)
Michael Carpenter
Sherry Comes
Carl Mohr (group head)
Michelle Neves
Carol Nicolaidis (75%)
Deirdre Roach
Diane Rogers
Rene Swindle
Robin Vaughan (40%)

Visitors

Ramesh Srivastava; University of Chicago; 1–21 July 1990; TDWR Project

Publications

Refereed Publications

CARBONE, R.E., *J.W. CONWAY, N.A. CROOK, and M.W. MONCRIEFF, 1990: Generation and propagation of a nocturnal squall line. Part I: Observations and implications for mesoscale predictability. *Mon. Wea. Rev. 118,* 26–49.

COOPER, W.A., and M.K. POLITOVICH, 1989: Reply to "Comments on 'Variability of the supersaturation in cumulus clouds' " by J. Witelford. *J. Atmos. Sci. 46,* 2752–2754.

CROOK, N.A., R.E. CARBONE, and M.W. MONCRIEFF, 1990: Generation and propagation of a nocturnal squall line. Part I. Observations and implications for mesoscale predictability. *Mon. Wea. Rev. 118,* 50–65.

——, T.L. CLARK, and M.W. MONCRIEFF, 1990: A numerical study of the Denver cyclone, Part I: Generation in low froude number flow. *J. Atmos. Sci., 47,* 2725–2742.

ELMORE, K.L., F.W. WILSON, JR., and M.J. CARPENTER, 1989: Recovering lost data: An adaptive least square outlier technique. *J. Atmos. and Oceanic Tech. 6(3),* 537–541.

*FUJITA, T.T., and J. MCCARTHY, 1990: The application of weather radar to aviation meteorology. In *Radar Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference* (D. Atlas, Ed.), AMS, Boston, Mass., 657–681.

GOODRICH, R.K., F.W. WILSON, and W. SPRATTE, 1990: Lawson's triangulation is nearly optimal for controlling error bounds. *SIAM Journal of Numerical Analysis 27(1),* 190–197.

HJELMFELT, M.R., H.D. ORVILLE, R.D. ROBERTS, J.P. CHEN, and F.J. KOPP, 1989: Observational and numerical study of a microburst line-producing storm. *J. Atmos. Sci. 46(17),* 2731–2743.

POLITOVICH, M.K., 1989: Aircraft icing caused by large supercooled droplets. *J. Appl. Meteorol. 28(9),* 856–868.

RASMUSSEN, R.M., P. SMOLARKIEWICZ, and *J. WARNER, 1989: On the dynamics of Hawaiian cloud bands: Comparison of model results with observations and island climatology. *J. Atmos Sci. 46(11),* 1589–1608.

ROBERTS, R.D., and J. W. WILSON, 1989: A proposed microburst nowcasting procedure using single Doppler radar. *J. Appl. Meteorol. 28,* 285–303.

*SCHWARTZ, B.E., C.F. CHAPPELL, *W.E. TOGSTAD, and *X.-P. ZHONG, 1990: The Minneapolis flash flood: Meteorological analysis and operational response. *J. Wea. and Forecasting 5(1),* 3–21.

*STITH, J.L., and M.K. POLITOVICH, 1989: Observations of the effects of entrainment and mixing on the droplet size spectra in a small cumulus. *J. Atmos. Sci. 46,* 908–919.

*WAKIMOTO, R.W., and J. WILSON, 1989: Non-super cell tornadoes. *Mon. Wea. Rev. 117,* 1113–1140.

WILSON, J.W., 1990: Aviation meteorology: Panel report. In *Radar in Meteorology* (D. Atlas, Ed.), AMS, Boston, Mass., 682–688.

Other Publications

BRISLAWN, K., F.W. WILSON, W.P. MAHONEY, G. WIENER, and R.K. GOODRICH, 1989: Microburst detection and display by TDWR: Shape, extent, and alarms. In *Preprint Vol., Third International Conference on the Aviation Weather System,* Anaheim, Calif., 28 January–3 February. AMS, Boston, Mass., 47–52.

BURGHART, C.D., P.J. WYNGAARD, P.H. HERZEGH, and J.W. WILSON, 1989: A program for optimization of meteorological radar scanning. In *Preprint Vol., 24th Conference on Radar Meteorology,* Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 573–576.

CHAPPELL, C.F., and *D.M. RODGERS, 1989: *Meteorological Analysis of the Cheyenne, Wyoming Flash Flood and Hailstorm of 1 August 1985.* NOAA Technical Report ERL 435 FSL1. NOAA, Boulder, Colo., 51 pp.

CORNMAN, L.B., P.C. KUCERA, M.R. HJELMFELT, and K.L. ELMORE, 1989: Short time-scale fluctuations in microburst outflows as observed by Doppler radar and anemometers. In *Preprint Vol., 24th Conference on Radar Meteorology,* Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 150–157.

CROOK, N.A., 1990: Numerical simulation of convective initiation along the Denver convergence and vorticity zone. In *Preprint Vol., Fourth Conference on Mesoscale Processes,* Boulder, Colo. AMS, Boston, Mass., 20–21.

——, 1990: A numerical study of atmospheric lee vortices with particular emphasis on the Denver cyclone. In *Preprint Vol., 5th Conference on Mountain Meteorology,* Boulder, Colo. AMS, Boston, Mass., 128–134.

——, R.W., T.L. CLARK, and M.W. MONCRIEFF, 1989: Comparison of numerically-simulated boundary layer circulations with radar observations during CINDE. In *Preprint Vol., 24th Conference on Radar Meteorology,* Tallahasee, Fla., 27-31 March. AMS, Boston, Mass., 30–33.

ELMORE, K.L., M.K. POLITOVICH, and W.R. SAND, 1990: The 11 July 1988 microburst at Stapleton International Airport, Denver, CO. In *Preprint Vol., 16th Conference on Severe Local Storms,* Kananaskis Park, Alberta, Canada, 22–26 October. AMS, Boston, Mass., 368–372.

—— and W.R. SAND, 1989: A cursory study of F-factor applied to Doppler radar. In *Preprint Vol., Third International Conference on the Aviation Weather System,* Anaheim, Calif., 29 January-3 February. AMS, Boston, Mass., 130–134.

GOODRICH, R.K., F.W. WILSON, and K. BRISLAWN, 1989: Divergence estimation by a single Doppler radar. In *Preprint Vol., Third International Conference on the Aviation Weather System,* Anaheim, Calif., 29 January–3 February 1989. AMS, Boston, Mass., 53–56.

*GOSLING, G.D., and J. MCCARTHY, 1989: Managing hazardous weather in airport operations of the 21st century. In *Proceedings, Looking to 2020. Airshow Canada Symposium on the Future of Air Transportation,* British Columbia, Canada, 8-10 August. Ministry of Advanced Education, Training and Technology, Province of B.C., 177–184.

JOHNSON, D.B., and R. M. RASMUSSEN, 1990: On the transition between wet-growth and dry-growth for graupel and hail. In *Preprint Vol., 1990 Cloud Physics Conference,* San Francisco, Calif., 23-27 July. AMS, Boston, Mass., 278–281.

*KLINGLE-WILSON, D., *S.H. OLSON, F.W. WILSON, W.P. MAHONEY, *S.D. SMITH, *A. WITT, and *M.D. EILTS, 1989: Gust front detection algorithm for the Terminal Doppler Weather Radar: Part 2, Performance assessment. In *Preprint Vol., Third International Conference on the Aviation Weather System,* Anaheim, Calif., 28 January–3 February. AMS, Boston, Mass., 31–34.

LUTZ J.S., S.E. YUTER, and J.W. WILSON, 1989: The workstation for analyzing four dimensional radar data. In *Preprint Vol., 24th Conference on Radar Meteorology,* Tallahassee, Fl., 27–31 March. AMS, Boston, Mass., 216–219.

MAHONEY, W.P., and K.L. ELMORE, 1989: The source region and evolution of a microburst downdraft. In *Preprint Vol., 24th Conference on Radar Meteorology,* Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 154–157.

——, F.W. WILSON, K. BRISLAWN, and M.K. POLITOVICH, 1989: Microburst detection by TDWR: Performance assessment. In *Preprint Vol., Third International Conference on the Aviation Weather System,* Anaheim, Calif., 28 January–3 February. AMS, Boston, Mass., 47–52.

MCCARTHY, J., 1989: Advances in Weather Technology for the Aviation System. In *Proceedings of the IEEE,* 77(11), 1728-1734. Also in *Proceedings, New Technology and the Aviation System,* Los Angeles, CA, 16-18 November 1988. Institute of Transportation Studies, University of California at Berkley, #UCB-ITS-P-89-1, 102–112.

—— and *A.L. HANSEN, 1990: An advanced aviation weather concept to serve the 21st century airspace system. Presented at 3rd International Symposium on Civil Aviation in the 21st Century, Paris, France, 14–16 November 1990. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo. 80307.

—— and W. SAND, 1990: Controller and pilot decision making in transmitting and receiving microburst wind shear alerts from an advanced terminal wind shear detection system. In *Proceedings, Conference on Weather Radar and Flight Safety,* Taipei, Taiwan, Republic of China, 10–11 May. Civil Aeronautics Administration M.O.C., Taipei, Taiwan, 197–206. Also presented at ICAO Human Factors Seminar, Leningrad, USSR. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo. 80307.

—— and R. SERAFIN, 1990: An advanced aviation weather system based on new weather sensing technologies. In *Proceedings, 43rd International Air Safety Seminar*, Rome, Italy, 19–22 November. Flight Safety Foundation, Arlington, Va.

MOORE J.A., C.K. MUELLER, and J.W. WILSON, 1989: A prototype control center for field programs and prospects for the future. In *Preprint Vol., 24th Conference on Radar Meteorology*, Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 605–608.

MUELLER C.K., and J.W. WILSON, 1989: Evaluation of the TDWR nowcasting experiment. In *Preprint Vol., 24th Conference on Radar Meteorology*, Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 224–227.

——, J.W. WILSON, and B. HECKMAN, 1989: Evaluation of the TDWR Aviation nowcasting experiment. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 212–216.

POLITOVICH, M.K., 1989: *FAA Icing Program. Draft Experimental Design.* 65 pp. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colorado 80307.

——, 1989: Measurements of hazardous icing conditions. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 159–163.

*POPA FOTINO, I.A., M.K. POLITOVICH, and J.W. HINKELMAN, 1989: Aircraft icing conditions detected by combined remote sensors: A preliminary study. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 173–177.

RASMUSSEN, R.M., W.A. COOPER, and M. MONCRIEFF, 1989: *The Dynamics and Microphysics of Colorado Front Range Winter Storms: Supercooled Liquid Water Production, Depletion and Detection.* An NCAR Scientific Proposal to the NCAR ATD Facilities Panels. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colorado 80307.

RASMUSSEN, R.M., N.A. CROOK, and C.J. KESSINGER, 1990: Precipitation bands in Colorado front range snowstorms: 15 November 1987 case study. In *Preprint Vol., Fourth Conference on Mesoscale Processes*, Boulder, Colo., 25–29 June. AMS, Boston, Mass., 63–64.

——,—— and ——, 1990: Precipitation development in Colorado front range winter storms. In *Preprint Vol., 1990 Conference on Cloud Physics*, San Francisco, Calif., 23–27 July. AMS, Boston, Mass, 758–764.

——, and M.K. POLITOVICH, 1989: *Winter Icing and Storms Project (WISP) Scientific Overview. Final Draft.* Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo. 80307. 42 pp.

RESEARCH APPLICATIONS PROGRAM, 1990: *Summary Project Report: Demonstration and Evaluation of a Wind Shear and Gust Front Detection and Warning System in 1989 Using the Terminal NEXRAD (Raytheon NEXRAD Prototype) Radar and Operational Low-Level Wind Shear Alert Systems at Stapleton International Airport* (J. Moore, Ed.). Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo., 80307-3000, 35 pp.

——, 1990: *Operations Plan for the Demonstration and Evaluation of a Wind shear and Gust front Detection and Warning System Using the Mile High Radar and Operational Low-Level Wind Shear Alert System at Stapleton International Airport* (J. Moore, Ed.). Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo., 80307-3000, 18 pp.

ROBERTS, R.D., and M.R. HJELMFELT, 1989: Evaluation of microburst nowcasting during TDWR 1987. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 206-211.

—— and ——, 1989: Multiple Doppler radar analysis of the 15 June 1988 Denver tornadoes. In *Preprint Vol., 24th Conference on Radar Meteorology*, Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 142–145.

SAND, W.R., 1989: Aircraft icing experienced over topographic features. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 379–380.

—— and C. Biter, 1989: *TDWR display experiences.* Preprint paper, 27th Aerospace Sciences Meeting, Reno, Nev., 9–12 January. AIAA-89-0807, AIAA, Washington, D.C., 8 pp.

—— and J. MCCARTHY, 1990: *Microburst wind shear: Integration of ground-based sensors to produce effective aircraft avoidance.* Presented at the Royal Aeronautical Society's Conference on Wind Shear, London, England, 1 November. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo. 80307.

—— and W.K. POLITOVICH, 1989: *Large supercooled droplets and how they relate to aircraft icing*. Presentation at the Third Interagency Airborne Geoscience Workshop, LaJolla, Calif., 21–24 February. Available from the Research Applications Program, NCAR, P.O. Box 3000, Boulder, Colo. 80307.

——, ——, J. McGinley and L. Osborne, 1989: A cooperative study of winter icing conditions in the Denver area. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 169–171.

——, ——, and R.M. RASMUSSEN, 1990: *A program to improve aircraft icing forecasts*. Preprint paper, 28th Aerospace Sciences Meeting, Reno, Nevada, 8–11 January. AIAA-90-0196, AIAA, Washington, D.C., 5 pp.

*SMITH, P.K., *H.D. ORVILLE, *J.L. STITH, *B.A. BOE, *D.A. GRIFFITH, M.K. POLITOVICH, and *R.F. REINKING, 1989: Evaluation studies of the North Dakota cloud modification project. In *Preprint Vol., Fifth WMO Conference on Weather Modification and Applied Cloud Physics*, Bejing, China, 371–376.

*TURNBULL, D., J. MCCARTHY, *J. EVANS and D. ZRNIC', 1989: The FAA Terminal Doppler Weather Radar (TDWR) Program. In *Preprint Vol., Third International Conference on the Aviation Weather System*, Anaheim, Calif., 29 January–3 February. AMS, Boston, Mass., 414–419.

*WAKIMOTO, R., C.J. KESSINGER, and *D.E. KINGSMILL, 1990: Forcing mechanisms of a low-reflectivity microburst. In *Preprint Vol., 16th Conference on Severe Local Storms*, Kananaskis Park, Alta., Canada, 22–26 October. AMS, Boston, Mass., 362–367.

*——, —— and *——, 1989: Visual and dual-Doppler analysis of low-reflectivity microbursts. In *Preprint Vol., 24th Conf. on Radar Meteorology*, Tallahassee, Fla., 27–31 March. AMS, Boston, Mass., 77–80.

WILSON, J.W., and R.D. ROBERTS, 1990: Vorticity evolution of a non-supercell tornado on 15 June 1988 near Denver. In *Preprint Vol., 16th Conference on Severe Local Storms*, Kananaskis Park, Alberta, Canada, 22–26 October. AMS, Boston, Mass., 479–484.

* An asterisk denotes a non-NCAR author.

Atmospheric Technology Division

Division Overview

Operational observing and associated facilities of the Atmospheric Technology Division (ATD) include research aircraft, remote sensing systems, atmospheric sounding instruments, automated surface systems, and interactive computing facilities, with skilled scientific and technical staff available for their operation and deployment. ATD's development capability resides primarily in its staff of scientists, engineers, and programmers. Development programs are routinely undertaken in collaboration with other NCAR divisions and university scientists.

The ATD technical staff routinely advises and assists users of its facilities in experimental design and planning for field programs, in sampling and measurement techniques, and, in some instances, in the design and fabrication of special equipment. Field data are quality assured and processed before distribution to users. Assistance in analysis of these data is also frequently included in the broad research support services provided by ATD.

The division supports a wide variety of scientific disciplines, including mesoscale meteorology, cloud physics, atmospheric chemistry, boundary-layer meteorology, and air-sea interactions. In recent years, use of the facilities by the atmospheric chemistry and oceanography communities has grown. There has been a trend toward deploying facilities over larger networks that emphasize the simultaneous study of a multiplicity of atmospheric spatial and temporal scales. These changes have had a direct influence on ATD's plans for the development of new systems. These plans include focusing on the needs for longer-range aircraft, improved field control and communications systems, and a wide variety of remote-sensing systems for more rapid and complete acquisition of four-dimensional observational data sets. One result is that ATD is in an excellent position to support future process studies of climate and hydrologic systems and biogeochemical dynamics in the U.S. Global Change Research Program, as well as mesoscale meteorological and cloud physical studies in the proposed U.S. Weather Research Program.

The division works closely with other NCAR divisions, universities, NSF, and other federal agencies to ensure that its current facilities and long-range plans provide for instruments and services most needed by the scientific community.

Division Goals

The goals of ATD are twofold:

- to provide unique, centrally administered observing facilities and associated data support services for use in research programs by the atmospheric and oceanic sciences communities

- to continually improve these facilities and services, and to develop next-generation facilities as community requirements dictate, by means of strong internal development programs.

Significant Accomplishments

- The division supported 23 field projects during the fiscal year. These projects included several major programs such as the Winter Icing and Storms Program (WISP) and the Hawaiian

Rainband Program (HaRP), each of which used several of ATD's facilities. HaRP in particular was a major effort by ATD, involving the Electra aircraft, 50 portable automated mesonet (PAM) stations, a field data analysis center, and the CP-3 and CP-4 C-band Doppler radars. These systems all worked well and the experiment was a significant success.

- Substantial progress was made on the Electra Doppler Radar (ELDORA) system, especially on the receiver-transmitter, high power amplifier, radar control, and data-processing modules. Agreements for collaboration in the development of ELDORA were reached with two French scientific organizations, whereby these organizations will design and build the ELDORA antenna and rotodome systems. Planning for the Electra tail modifications was finalized, a request for proposal was prepared and distributed, and the selection of a contractor was initiated.

- The atmosphere-surface turbulent exchange research (ASTER) facility became operational during fiscal year (FY) 90. The system is now available to the community to provide tower-based measurements of turbulent fluxes of momentum, sensible heat, and water vapor in the atmospheric surface layer, and to support a broad range of observational research on the structure of the surface layer. In addition, the new system is capable of supporting user-supplied instrumentation for the measurement of fluxes of trace chemical species by a variety of methods including eddy correlation, gradient transfer, and conditional sampling. Following an extensive test period at the Marshall field site, ASTER's first deployment was to Carpenter, Wyoming, to support the Full Look at Turbulent Kinetic Energy (FLAT) field program.

- Development of a sophisticated new atmospheric sounding system, called an integrated sounding system (ISS), got under way. The new system is being developed jointly by ATD and NOAA's Aeronomy Laboratory. The purpose of ISS is to obtain high-resolution profiles of atmospheric variables through the troposphere and stratosphere. The ISS concept involves integrating the measurements from a diverse suite of active and passive remote sensors, together with ground-based and upper-air in situ sensors. The initial ISS development now under way is focusing on a limited system that will meet the basic requirements of the Tropical Ocean and Global Atmosphere (TOGA) program's Coupled Ocean-Atmosphere Response Experiment (COARE). The limited ISS for COARE will consist of a UHF Doppler wind profiler, a radio acoustic sounding system (RASS), an Omega upper-air sounding system, and a surface meteorological system.

- Two of ATD's research aircraft, the King Air and the Electra, received new data systems. These Sun-based systems include high-level windowing software to make them easy to use, and have considerably higher performance than the older aircraft data systems. In addition, they are roughly half the size and weight of the older systems. The Electra's navigation equipment was also upgraded with the installation of a new laser-based inertial navigation system and the addition of a new global positioning system (GPS).

- A major restructuring of ATD was completed, involving the formation of two new groups, the Remote Sensing Facility and the Research Data Program. These organizational adjustments have been made to allow the division to provide better support to global change research. With these changes, ATD is able to place greater emphasis on remote sensing, multiplatform data packaging and integration, and satellite data access and validation. The division also continued to develop stronger interactions with other NCAR divisions and with university research and educational programs. The number of joint appointments with other NCAR divisions rose to 8, while 11 intermediate and long-term visitors worked with ATD's staff during the year on new instrumentation and collaborative research projects.

Research Aviation Facility

Mission and Goals

The Research Aviation Facility's (RAF) mission is to develop and operate instrumented research aircraft for the atmospheric science community at a level of sophistication and operational complexity not generally available elsewhere.

RAF goals are:

- to operate the research aircraft safely and reliably. Aircraft safety is of paramount importance in RAF's strategy.

- to provide research aircraft users with comprehensive support, so that RAF participates as an integral part of the scientific and technical research team. RAF assists in planning and conducting field experiments, provides data processing and quality control, documents instrumentation characteristics and limitations, and, when appropriate, assists during the analysis phase of experiments.

- to anticipate the future scientific needs of the atmospheric science community and to develop research systems (aircraft, instruments, and data acquisition systems) suited to those needs. RAF's scientific and engineering staffs monitor research needs and technological developments that can be applied to those needs.

Aircraft Fleet and Instrumentation

During FY 90, the research aircraft fleet consisted of:

- a Beechcraft Super King Air Model B200T, a very flexible and versatile twin-engine turboprop aircraft that can be equipped to support studies in cloud physics, boundary-layer meteorology, mesoscale dynamics, atmospheric chemistry, oceanography, etc.

- a North American Rockwell Sabreliner Model NA265-60, a twin-engine jet capable of a maximum flight altitude of about 41,000 ft (12,600 m). The Sabreliner is often used for studies of atmospheric chemistry in the upper troposphere and lower stratosphere, ice particles at high altitudes, upper tropospheric and lower stratospheric dynamics, and tropospheric-stratospheric exchange processes.

- a Lockheed Electra Model L-188C, a four-engine turboprop aircraft used for missions requiring long ranges, large payloads, or extended flight over water. This aircraft is often used to study tropospheric chemistry or meso-synoptic-scale storms and cloud systems.

These aircraft have sophisticated data acquisition and display systems, inertial navigation systems, and gust probes for the measurement of wind components and turbulent air motions, and have basic systems for the measurement of state parameters such as temperature, pressure, and dew point. All can be equipped with probes that detect cloud and precipitation hydrometeors and with sensors that record infrared and visible radiation, liquid water content, concentrations of some chemical species, surface temperature, photographic images, and high-frequency fluctuations in temperature and water vapor. In addition, the platforms are designed to be flexible; user-supplied or other specialized equipment can be installed in the aircraft and integrated with the data systems to meet particular needs, generally at modest program cost.

Field Support and Test Projects

During FY 90, RAF supported 17 university, NCAR, or other agency projects, flying 184 separate flights for a total of 543 flight hours. Supported field programs included studies of storm dynamics, atmospheric chemistry, cloud physics, planetary boundary-layer processes, and air-sea interaction, and tests of newly developed instrumentation. Some of the field programs are described below; research use of the RAF aircraft is summarized in Tables 1 and 2.

Instrument Test Program. A number of new instruments were tested on the NCAR King Air, Sabreliner, and Electra. These included a new in-cloud thermometer probe constructed by Paul Lawson (visitor, SPEC, Inc.), and an improved version of the cloud particle spacing monitor developed by Darrel Baumgardner. During the HaRP project two dye chemiluminescence fast-response ozone analyzers were tested, and the counterflow virtual impactor (CVI) instrument was evaluated. An Ophir hygrometer was intercompared with the NCAR cryogenic frost-point hygrometer, and advanced dropwindsondes developed by ATD's Surface and Sounding Systems Facility (SSSF) as well as the new NCAR ice crystal impactor were also tested. Finally, the new King Air data display and recording system was successfully tested and evaluated.

Table 1. Summary of Disposition of FY 90 Flight Requests.

	No. of Projects		No. of Hours			No. of Missions
	Requested	Flown	Requested	Allocated	Flown	
Sabreliner N307D	7	6	207	149	134.7[1]	71
Electra N308D	6	4	556	284	280.6	62
King Air N312D	12	7	526	109	127.7	51
Total	25	17	1289	542	543.0	184

[1]Includes 48.1 hours of cost-recovery flight time.

Table 2. Summary of FY 90 Aircraft Use.

User	Project	Aircraft[1]	Science[2]	Research Period	Hours Flown
Twohy et al./NCAR	Cloud Droplet Chemistry	KA	CP,AC	9/12–10/9/89	30.0[3]
Griffith/NCAR	Data Display Test	KA	E	10/89	1.8
Hallett/DRI	A/C Research Training	EL	AC,BL,CP,D	10/16–10/27/89	17.7
RAF/NCAR	Instr. Intercomparison	EL	E	10/89	1.2
RAF/NCAR	Instr. Intercomparison	SL	E	10/89	1.8
Cooper/NCAR	Ice in Wave Clouds	KA	CP	11/15–12/7/89 3/12–3/30/90	19.4
Hagen/U. of Mo. Heymsfield/NCAR	Spontaneous Ice Nucleation	SL	CP	11/7–12/17/89	43.1
Grossman/CIRES Kuettner/NCAR	Conv. Waves Over Ocean	KA	BL,MS, D	1/16–2/14/90	53.3
Grossman/CIRES Kuettner/NCAR	Conv. Waves Over Ocean	SL	MS,D	1/16–2/14/90	40.6
Gardner/U. of Ill.	Sodium Lidar	EL	UPPR ATM	3/20–4/20/90	81.6
Lawson/NCAR	In-cloud Thermometer	KA	CP,E	4/24–5/10/90	20.6
Lauritsen/NCAR	Dropwindsonde Test	SL	E	5/90	1.1
Ridley/NCAR	ROSE-AIR[4]	SL	AC	6/12–30/90	36.5
Moncrieff et al. /NCAR	HaRP	EL	AC,BL, MS,CP	7/16–8/25/90	180.1
Huebert/U. of R.I.	Particulate Airborne Inlet Research	KA	CP,E,AC	9/90	0.8
Cole/NCAR	L2D2 Test	KA	E	9/90	1.8
Miller/Ophir Corp.	Instr. Test	SL	E	9/17–28/90	11.6

[1]EL = Electra
KA = King Air
SL = Sabreliner

[2]AC = Atmospheric chemistry
BL = Boundary layer
CP = Cloud physics
D = Atmospheric dynamics
E = Evaluation of instruments
MS = Mesoscale

[3]FY 90 portion

[4]Rural Oxidants in the Southern Environment experiment

Cloud Droplet Chemistry Experiment. This program, conducted during September-October 1989, was a collaborative study of droplet chemistry in stratocumulus clouds off the California coast. It was led by Cynthia Twohy (graduate research assistant), Robert Charlson (University of Washington), and Barry Huebert (University of Rhode Island). Two different collection methods for cloud water samples were used: Mohnen slotted rods, which collect a bulk cloud water sample, and the CVI, which allows size-selective droplet sampling. Chemical results from the two methods were compared and used to investigate how droplet chemistry is affected by different cloud processes. The experiment was also used to better characterize the CVI as well as another new instrument which collects aerosol particles on filters outside the aircraft. In the final data analysis, the microphysical measurements will be integrated with the measurements of cloud radiative properties to study possible relationships.

Aircraft Research Training (ATRAIN). As a pilot experiment, 12 graduate students from the University of Nevada at Reno (UN-R), participated in a series of research flights. The students, under the guidance of John Hallett (UN-R) and NCAR staff, participated in designing and planning research missions and in directing the research flights. Several local research flights were conducted during 16–27 October 1989. Each flight targeted a specific weather phenomenon for investigation. One flight examined cloud physics parameters within precipitating supercooled upslope stratus. A second flight monitored the breakup of the surface-based inversion in the Denver basin, while a third flight tracked the motion and downwind dispersion of the Denver pollution plume. Another flight provided intercomparison data with the NCAR Sabreliner along with high-altitude penetrations of mountain waves and lenticular clouds. Following the flights, the students were introduced to data quality control methods and data-processing and analyzer techniques. In addition to accomplishing the processing and analysis of the collected data set, on nonflight days the students attended lectures given by NCAR staff on a series of research topics.

This program was part of a formal course in atmospheric observations for students working for Ph.D. or M.S. degrees. This course will be assessed to determine whether future courses at NCAR or at other national observing facilities would be beneficial to students from UCAR universities as practical training in atmospheric measurements and instrumentation.

Spontaneous Ice Nucleation Studies. Andrew Heymsfield (Mesoscale and Microscale Meteorology Division, or MMM), and Donald Hagen (University of Missouri-Rolla) used the Sabreliner to study cloud nucleation properties. High-altitude cloud-air sampling began on 9 November 1989 in the Colorado Front Range area. These air samples were obtained in lenticularis clouds for analysis on the ground for aerosol content and nucleation potential. During the air sampling, ice crystal samples were obtained for later laboratory studies, including tests at the University of Missouri cloud chamber located in Rolla. Problems with the airborne data system (ADS) were encountered during the November flights. After a considerable effort, these problems were solved for the December flight period. The research effort continued through 17 December 1989.

Ice Formation in Wave Clouds. William Cooper used the NCAR King Air during portions of November/December 1989 and March 1990 to study ice formation in wave clouds. The primary objective of these flights was to collect data that could be used to study the nucleation processes responsible for ice formation along airflow trajectories. This objective was met on several flights. During the March field phase the new NCAR ice crystal impactor was tested.

Convective Waves over the Ocean. Under the direction of Robert Grossman (University of Colorado) and Joachim Kuettner (MMM), the NCAR King Air and Sabreliner aircraft were operated from 19 January to 19 February 1990 in support of the Convective Waves over the Ocean program. This program was based out of the NASA Wallops Island Flight Facility and involved concurrent operation of both of the NCAR aircraft and NASA's lidar-equipped Electra. The research targeted the formation of atmospheric gravity waves caused by cold air advection over the warm surface water of the Gulf Stream.

The NASA Electra provided midlevel turbulent structure measurements along with remote lidar observations of the eddy activity as manifested by aerosol structure within the convective boundary layer. The NCAR King Air and Sabreliner were used to provide concurrent measurements of the three-dimensional structure of the gravity wave systems extending from the boundary layer to the upper troposphere. Although the distinctive cloud street patterns normally associated with the gravity wave phenomenon failed to materialize, a series of idealized convective wave and airmass modification case studies were flown during the extended research interval. Wave patterns in the vertical velocity profiles and the boundary-layer aerosol layers were documented from the boundary layer up through 25,000 ft (7,700 m). Despite the unseasonably warm weather encountered during the research period, the case studies included in the data set are quite remarkable and should provide valuable information on the formation and structure of gravity waves. Several intercomparison missions were flown to cross reference the performance of the three gust probe systems.

Sodium Lidar Hawaiian Campaign. This experiment was led by Chester Gardner (University of Illinois) as part of the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program. The primary instrument of this experiment was the CEDAR sodium lidar. Although installing this large, complex instrument in the Electra presented major technical challenges, this task was performed successfully.

The Electra was operated out of Maui, Hawaii, from mid-March through the mid-April 1990 to study atmospheric gravity waves in the upper atmosphere. Gravity waves and tides play a major role in determining the large-scale circulation and structure of the middle atmosphere. Gravity waves are believed to be the major source of energy transport between the upper and lower atmosphere. Turbulence caused by breaking waves has a significant influence on the thermal and density structure of the mesosphere and thermosphere.

The high-power sodium lidar used in this program measured resonant backscattering from naturally occurring sodium in the 80–105-km region of the thermosphere. These data were used to identify and track gravity waves in this region. Molecular backscattering was used to track gravity waves and profile temperature in the 20–70-km region of the stratosphere and mesosphere. Complementary measurements were conducted by piggyback investigators Rick Niciejewski and Jeng-Hwa Yee (University of Michigan). Their instruments observed hydroxyl and diatomic oxygen airglow emissions and temperature in the same altitude region covered by the sodium lidar measurements.

In-Cloud Thermometer Studies. Lawson used the NCAR King Air in the Corpus Christi, Texas, area for his in-cloud thermometer studies. The objective of this field program was to test two newly developed in-cloud temperature probes. Using the data obtained, these new probes were evaluated to determine their susceptibility to errors arising from sensor wetting in warm clouds. The second goal was to conduct a comparison with other thermometers, such as the radiometric (Ophir II) thermometer and other currently used immersion-type sensors like the Rosemount 102E and reverse flow temperature probes. As a piggyback effort, the performance of the forward scattering spectrometer probe (FSSP), the particle spacing monitor (PSM), and the microwave refractometer was also tested. Although the weather was unusually cool and rainy during this program, enough in-cloud data were obtained to achieve the research objectives.

Rural Oxidants in the Southern Environment. The NCAR Sabreliner was deployed for Brian Ridley (Atmospheric Chemistry Division, or ACD) from 12 to 28 June 1990 in support of the Rural Oxidants in the Southern Environment (ROSE) program. This was a collaborative effort between ACD and the NOAA Aeronomy Laboratory designed to determine the role of hydrocarbons and oxides of nitrogen (NO_x) in the formation of ozone in the rural southern environment. An extensive array of chemical and meteorological measurements was made at the primary ground site located within a remote tree farm in west central Alabama. The Sabreliner aircraft was equipped with nitric oxide (NO), nitrogen dioxide, nitrogen trioxide, total odd nitrogen (NO_y) and hydrocarbon sampling equipment in order to provide measurements on the regional transport and the vertical structure of the key constituents. Weather patterns were generally cooperative, but no high ozone cases were observed at the ground station during the Sabreliner operational period. A preliminary review of the aircraft measurements showed signs of unexpectedly complex structure in both the horizontal and vertical profiles of the chemical constituents.

Hawaiian Rainband Project. The main objectives of HaRP were to study the formation of rainbands and the associated mesoscale airflow around the island. A central goal was to document and understand the structure of the rainbands by way of understanding the dynamic and microphysical processes that interact to force the circulations that form the windward rainbands. One of the purposes of the project was to model the simple rainbands produced in the tropical climate in order to understand rainband formation in more moderate climates, where snow and ice crystals result in more complex rainband systems.

The island of Hawaii provided an ideal environment for studying the rainbands because of its consistent diurnal weather patterns during the summer and relative isolation from major land masses. Trade winds interacting with the island result in almost daily rainbands, which form offshore in the morning and deposit precipitation on the windward side of the island later in the day. The two large volcanos on Hawaii, Mauna Loa and Mauna Kea, play a key role in the formation of the rainbands, as well as delineating the dry climate on the leeward side of the island and the rain forest on the windward side.

The field phase of HaRP was conducted from 15 July to 25 August 1990 in Hilo. More than 100 people, including some 25 principal investigators (PIs), participated in the experiment. The scientific team included participants from NCAR; a number of universities, including Hawaii, Illinois, Washington, Yale, McGill, and the New Mexico Institute of Mining and Technology; NOAA; and institutions in France, Australia, and Canada.

NCAR supported the experiment with the Electra research aircraft, two C-band radars (CP-3 and CP-4), and 50 PAM stations installed around the island of Hawaii. A NOAA profiler, a tethersonde, supplementary sounding systems, and a chaff-dispensing aircraft were also used. Weather conditions were suitable throughout the experiment, and all facilities functioned smoothly, with very few problems. The investigators believe that almost all HaRP objectives can be addressed well with the excellent data set from the field program.

Instrumentation Development Activities

RAF scientists conduct research and development to maintain the NCAR research aircraft as state-of-the-art research facilities and to develop new capabilities that match community measurement needs. The current strategy guiding RAF development activities focuses on three areas: development or acquisition and calibration of new in situ instruments, development of new airborne remote sensors, and improvements in the accuracy and reliability of existing instruments providing basic measurements of temperature, pressure, humidity, and wind. Several of these instrumentation development activities are summarized below.

Investigations of Flux Sampling Strategies (Cooper, Project Leader). Future studies in atmospheric chemistry will require new measurements of the fluxes of chemical species. From aircraft, most such measurements are now made by the technique of eddy correlation, which requires fast-responding sensors for both wind and the chemical species. To avoid the need to develop a host of new, fast-responding chemical sensors, an alternative approach has been investigated in which samples would be taken intermittently rather than at high rate. Theoretical considerations show that, if each sample is taken over a short distance in space, the accuracy of the measurement remains similar to that available from eddy correlation even if the individual samples are spaced as far apart as the integral scale of the turbulence.

In simulations of this intermittent-sampling technique, conventional high-rate measurements were used to show that results comparable to those from eddy correlation could be obtained using this new technique. Therefore, a proof-of-concept experiment has been designed to test the feasibility of this approach, and a prototype system has been designed for this field test. If successful, this development has the potential to facilitate many new measurements of the fluxes of chemical species, and thus to play an important role in future programs in atmospheric chemistry.

Small Ice Detector (Cooper, Project Leader.) Current airborne sensors are inadequate in their ability to detect small (<100 μm) hydrometeors, yet many crucial questions relating to clouds and radiation in the atmosphere involve such hydrometeors. For example, crystals of this size are of the highest importance in cirrus clouds, where they dominate the radiative interactions. Also, the development of precipitation in clouds involves the growth of hydrometeors through this size range, and our inability to properly measure these hydrometeors has inhibited studies of precipitation development.

To address this need, MMM and RAF personnel have collaborated on the development of a new detector based on an impactor and a video camera. This probe, mountable in a Particle Measuring Systems (PMS) enclosure, collects hydrometeors on a transparent film and then moves them to a viewing area where they can be recorded on video tape through a microscope. The impaction technique is used to provide a suitable sample volume, and microphotography is used to provide adequate size resolution to see 10-μm objects and to determine shapes of larger hydrometeors.

This system has been flown in two test programs, where it has been demonstrated that the sampling technique is feasible. Work is continuing to improve the optical components, and future use of this probe is planned in programs like the First ISCCP (International Satellite Cloud Climatology Program) Regional Experiment (FIRE), where the measurements it can provide will be of critical importance.

The NCAR Airborne Infrared Lidar System (Ron Schwiesow, Project Leader). NAILS is a multiyear effort to develop a Doppler lidar for measuring winds in the clear atmosphere. NCAR-designed components have now been fabricated and installed to convert the lidar into a heterodyne system capable of measuring the Doppler shift from particles in the atmosphere moving with the wind. The new Doppler configuration was tested and improved in preparation for initial flight tests scheduled for January 1991.

A new laser resonator has been developed to reduce the coupling of vibration from the laser gas transport fans to the resonator structure, and a special-purpose detector allows measurement of the offset frequency between the pulsed transmitter and continuous-wave local oscillator lasers. With a measurement of the offset in the first microsecond of the signal return, a coherent radio-frequency oscillator can be set to represent the frequency of a zero-velocity return for each pulse. This innovative technique is important because it allows
the data-processing electronics to improve the accuracy of a velocity estimate by averaging autocorrelation functions, rather than velocity estimates, from a number of pulses. Averaging autocorrelations reduces the influence of low-level signals on the result.

The signal and data-processing electronics, which include the same high-speed digital signal processing chip and analog-to-digital converters used in the RP-7 radar processor in ATD's Remote Sensing Facility, were completed this past year for the lidar. A number of options for the analog section of the signal-processing electronics are currently being evaluated.

Ultraviolet Hygrometer (Schwiesow, Project Leader). Results from flight tests of a prototype instrument based on a new concept for an ultraviolet hygrometer have been evaluated. This instrument uses two paths and two wavelengths to correct for changes in lamp output and window transmission that result from the rapid changes in the environment of an airborne instrument. The test data demonstrate the necessity for two wavelengths, especially near cloud boundaries, and two paths, especially when the ambient temperature is changing rapidly.

A journal submission, presently in internal review, describes the principle of operation and preliminary test results. Based on experience with the prototype, an effort is under way to make a number of improvements in the instrument to enhance data quality, to increase ease of manufacture, and to facilitate maintenance.

Fast Response Ozone Instrumentation (Gregory Kok, Project Leader). As part of the ongoing work on the development of fast-response ozone instrumentation, a conventional NO fast-response ozone instrument has been constructed. This instrument has been compared with the dye chemiluminescence fast-response ozone instrument that is presently under development at RAF. Both of these instruments were flown during the HaRP project on the NCAR Electra. The dye chemiluminescence instrument has considerably lower noise than the conventional instrument, but a response time of about 3 Hz, which is a factor of two slower than the conventional instrument. The HaRP measurements appear to be good enough to allow the flux of ozone to the ocean surface to be determined.

Inertial Navigation System (INS) Replacement (Richard Friesen, Project Leader). RAF has evaluated commercially available inertial navigation platforms this past year as potential replacements for the aging Litton LTN-51s currently in use. These platforms are an integral part of the air motion measurement systems on all of the NCAR aircraft. They provide measurements of aircraft attitude angles, three axis accelerations, and position which are then used in conjunction with other air motion measurements (i.e., from the gust probes) to obtain a three-dimensional wind vector. The Honeywell

Laseref SM, an inertial reference system with ring laser gyroscopes, has been selected, and units will be installed in the Electra and King Air in early 1991.

These systems, in conjunction with the NAVSTAR GPS, should give aircraft position accuracy to 50 m and wind accuracy to 0.5 m/s. High reliability is a very important feature of these systems, in contrast with the rather poor reliability of mechanical gyro systems. RAF will be working with other organizations to develop Kalman filters and other software for combining position measurement information from several platforms to obtain optional solutions.

Airborne Data Display System Upgrade (Mary Griffith, Project Leader). Upgrades to the NCAR airborne data display system are now being installed in the Electra. The new system replaces the old HP1000 computer with multiple Sun SPARCstations. The XView window system is used to provide the user with four display areas, each of which can contain up to four graphics displays or can list alphanumeric data. The system comes up with preselected default displays which can be reconfigured by the user at any time. Flight testing will be conducted during January 1991, after which time the system should be ready for supporting research.

Another version of this Sun display system was installed on the King Air in November 1989 and has successfully supported five field projects. A Sun SPARCstation is also now available to provide ground station support for the Electra or King Air. Data analysis and display software is being converted to a window-based format as quickly as possible to provide the user with a consistent interface to all the systems.

Particle Spacing Monitor (Baumgardner, Project Leader). Cloud microphysical studies have become more focused on the evaluation of very small scale processes, especially for the purpose of gaining a better understanding of the effects of entrainment and mixing on droplet growth. A system has been developed at RAF that records the individual sizes and arrival times of droplets that are measured by the PMS FSSP. This system differs from the usual method of recording data from this probe in that conventional systems take the average of a large number of droplets over fixed periods of time. This unique method of preserving the information about individual droplets allows spatial resolutions of less than a millimeter to be studied. The new system was flown on the Electra during the HaRP project and collected almost 135 hours of data in the rainbands near the island of Hawaii. Analysis of these data is currently in progress.

Counterflow Virtual Impactor (Twohy, Project Leader). The CVI has been further developed for use on the Electra and flown during the HaRP project. This instrument collects droplets above a certain size in a cloud and separates them from surrounding interstitial gases and aerosol particles. The droplets are then evaporated, allowing analysis of residue particles and volatile gases by various methods. Measurements taken during HaRP from the CVI are currently being analyzed and will be compared with interstitial cloud condensation nucleus (CCN) measurements made during this same period by James Hudson (Desert Research Institute).

In-Cloud Temperature Measurement (Lawson, Project Leader). A newly developed fast-response temperature sensor has been developed as an alternative to the reverse flow probe for measuring in-cloud temperature. This instrument is designed in the shape of an egg, with thermocouples located on the aft section behind the point of turbulent separation of the boundary layer. This design is intended to cause droplets to remain embedded in the separated flow, leaving the sensors unwetted. Test flights were conducted in maritime clouds in May 1990, and again during the HaRP project. Preliminary results indicate that the response time of this probe is better than that of any of the other presently operated airborne sensors and that under some cloud conditions, the sensor remains unwetted. However, additional evaluation and testing are needed to understand why wetting took place under some environmental conditions.

Instrumentation Development for the Sailplane (James Dye, Project Leader). A major rewiring of the power distribution network in the sailplane has been accomplished to prepare the sailplane for a new data acquisition and recording system to be installed in the coming year. The goal is to have both the recording system and an interface to a GPS ready for use during the Convection and Precipitation/Electrification (CaPE) experiment in July 1991. The new data system will be installed following this project.

RAF Staff Research Activities

During the summer of 1990, a group of scientists from MMM collaborated with a number of other scientists in ATD and from outside NCAR to plan and conduct the field phase of HaRP. Several of the RAF scientific staff were active participants in this project. Their interests and activities are described below.

Cooper, a principal investigator as well as a major organizer of HaRP, is mainly interested in the thermodynamics and kinematics of the formation and evolution of the Hawaiian rainbands. The combination of dual Doppler radar and in situ aircraft measurements of the rainband structure provides an extensive data set that will be combined with models to form a more complete picture of the process by which rainbands evolve.

Baumgardner, also one of the principal investigators, investigated the role of mixing and entrainment, small-scale turbulent fluctuations, and fine-scale droplet structure on the evolution of cloud droplets. He is using measurements from the PSM and high-rate turbulence measurements to study these processes at very small scales.

Kok made airborne measurements of hydrogen peroxide and methylhydroperoxide during HaRP. These were the first specific measurements of these species in a remote marine environment, and showed that the concentration of hydrogen peroxide with respect to methylhydroperoxide increases with height in the boundary layer.

Twohy studied the concentration of cloud nuclei contained in cloud droplets during HaRP using the CVI. These data are being analyzed to evaluate cloud microphysical processes as related to the background interstitial CCN and to study the relation between cloud droplet size and CCN concentration.

Dye mounted electric field mills on the Electra to measure the vertical component of the atmospheric electric field during HaRP. Very few measurements of this type have been made in maritime clouds. Analysis of the data is currently in progress.

Although HaRP was the main event of the year, the scientific staff of RAF were also involved in a number of other research activities. Cooper, in collaboration with Heymsfield, conducted flight programs to observe the microphysical characteristics of wave clouds, with particular emphasis on the formation of ice in such clouds. The resulting data will be used to study homogeneous and heterogeneous nucleation processes and the evolution of droplet spectra in the wave clouds. Early results include the documentation of a rapid homogeneous nucleation process, occurring approximately as expected from laboratory experiments, and the finding that in many cases the concentrations of heterogeneously formed ice particles are surprisingly low even near the homogeneous nucleation threshold. The patterns of ice formation indicate a rapid onset of nucleation in both homogeneous and heterogeneous cases. Analyses and additional data collection are continuing.

Cooper is also involved with WISP, which is a joint NCAR-NOAA-university project sponsored by NSF and the Federal Aviation Administration (FAA), coordinated principally by NCAR's Research Applications Program (RAP), to study the production and depletion of supercooled water in wintertime storms and the associated icing hazards to aircraft. His participation in this program is focused on improving the scientific understanding of the dynamical and microphysical processes involved, through documentation of the microphysical characteristics and kinematic structures and through modeling of the dynamical evolution and the formation of precipitation in these storms.

Schwiesow's research has been in the area of remote-sensing technology and its applications. These efforts have resulted this year in a paper on lidar measurements of a sloping aerosol layer intersecting a marine stratocumulus cloud deck, which has been accepted for the *Journal of Applied Meteorology* (JAM), and a paper on the NCAR Doppler lidar development that was given at the Seventh American Meteorological Society (AMS) Symposium on Meteorological Observations and Instrumentation in January 1991. Schwiesow also investigated applications of differential absorption lidar (DIAL) techniques for profiling atmospheric constituents, and contributed to a report outlining options for ATD in developing instruments to make these kinds of observations.

Twohy's two-year visitor's term at RAF ended in July, and she currently holds a graduate research assistantship from the Advanced Study Program (ASP) as she pursues her Ph.D. through the University of Washington. Her primary study is concerned with analysis of data taken with the CVI; however, she has also evaluated the results of measurements to determine the structure of flow around the King Air and its effects on measurements of liquid water content. She and Diana Rogers presented this work at the Seventh AMS Symposium on Meteorological Observations and Instrumentation.

Edward Brown has been analyzing results of an airborne altimetry study to evaluate the accuracy of the radar altimeters used on NCAR aircraft. He has submitted a paper to the *Journal of Atmospheric and Oceanic Technology* that summarizes his results. Brown has also written a paper to be published as an NCAR Technical Note that evaluates the accuracy of the radome systems used for measuring winds on NCAR aircraft. Both the altimeter and radome studies are part of a larger effort headed by Brown to evaluate the measurement uncertainties of all of the instrumentation operated by the RAF.

Baumgardner has been continuing the work that he began while a scientific visitor at the German Research Aerospace Establishment in 1989. He has been analyzing airborne aerosol measurements taken in cumulus clouds in northern Germany, and presented a paper at the 1990 Cloud Physics Conference and a seminar at the University of Washington on his results. He has also been analyzing the microstructure of an upslope storm in southern Germany, using measurements taken with the NCAR King Air in 1987. He presented some of these results at the 1990 Cloud Physics Conference. Baumgardner has been working to improve airborne measurements of aerosols and has proposed the development of a new instrument with greatly enhanced measurement capabilities. He is continuing his role in improving current microphysical measurements, and has developed new techniques for analyzing data from the PMS-2D probe using fractal analysis. He presented these results at the Seventh AMS Symposium on Meteorological Observations and Instrumentation.

Surface and Sounding Systems Facility

Mission and Goals

The mission of the Surface and Sounding Systems Facility (SSSF) is to provide surface-based in situ and sounding measurements and associated data-processing and analysis software in support of atmospheric research. The facility also engages in a nominal amount of related scientific research to maintain and support a leadership role in the operation and development of state-of-the-art measurement systems. SSSF engages in the following major activities:

- operation of advanced surface- and upsonde/dropsonde-based immersion-sensing systems to support field research of atmospheric scientists.
- development of new surface and sounding systems in cooperation with other ATD facilities, NCAR divisions, NOAA, and universities.
- development of new data telemetry systems to support ATD's field data communications needs.
- development and maintenance of editing, display, and applications software.
- development of operational and analytical techniques for optimum use of field facilities, and transfer of these techniques to the atmospheric sciences community. These techniques include sensor calibration, instrument deployment, data collection, and data analysis methods.
- scientific research and engineering development to support, demonstrate, and advance these capabilities.

The emphasis of the facility has been to support mesoscale and boundary-layer experiments in keeping with national scientific interests in atmospheric chemistry, mesoscale precipitation systems, cumulus convection, boundary-layer processes, and air-surface interaction. SSSF has focused significant resources over the past year on several important developments of improved and advanced observing systems, while continuing to support all requests for field measurements. Our strategy has been to meet all community requests for field support and to optimize the use of remaining facility resources to develop new observing systems that will meet the field-support requirements of future major experimental programs of national interest, such as the Stormscale Operational and Research Meteorology (STORM) program, the Global Tropospheric Chemistry Program, and TOGA/COARE.

Field Program Support

Arctic Boundary-Layer Experiment (ABLE-3B). This NASA-sponsored experiment was led by David Fitzjarrald of the State University of New York at Albany, who served as PI. The study focused on the emission and deposition of trace species in the subarctic boreal and tundra regions of northeastern Canada. Surface observations were provided by a network of four PAM-II remote stations located around turbulent flux measurement sites near Schefferville, Quebec. The PAM stations documented the low-level thermodynamic and flow regimes and provided valuable information on the terrain-influenced microclimates of the region. The measurement period of ABLE-3B began in the middle of June, at the time when the northern lakes are beginning to melt. The observations continued through the summer season and into the return of colder weather, in mid-August. The PAM network proved important in relating the flux measurements to the propagation of local weather phenomena. Because the PAM stations spanned a significant range of elevations, significant valley flows and strong stratification were also documented.

Baruch. SSSF has maintained a single PAM-II remote station at the Baruch Marine Laboratory (jointly sponsored by the University of South Carolina and Clemson University) near Georgetown, South Carolina, throughout FY 90. The station was installed at the site in response to an appeal for help following damage from the passage of Hurricane Hugo. As an NSF Long-Term Ecological Research site, the lab had maintained climate records since 1982. It was important to maintain a nearly continuous record following the destruction of the Baruch equipment by Hugo. To quickly meet the needs, a PAM station was installed on 14 October 1989. The station has been in operation continuously since that time, requiring only two maintenance visits by SSSF. The only other significant down time occurred when parts of the station were removed by Baruch personnel for safekeeping when the area was threatened by another hurricane in the fall of 1990. The station will remain in place until a replacement can be obtained by Baruch.

Experimental Cloud Lidar Pilot Study (ECLIPS). The primary measurement objective of this program was to gather information on the vertical distribution of clouds and their optical properties (particularly the cloud-base altitude) with the objective of parameterizing the downwelling solar flux from satellite measurements. A high-resolution interferometer sounder (HIS) developed by William Smith (University of Wisconsin) was used to measure the downwelling radiance. A second objective of the study was to test the utilization of the interferometer for atmospheric profiling. A single cross-chain Loran atmospheric sounding system (CLASS) station was installed at the University of Wisconsin campus in Madison during November 1989, and 50 upper-air soundings were made by members of the university staff. The CLASS soundings provided data that were used to calibrate the HIS temperature and water vapor profiles. These data together with satellite-based radiance measurements provided a full characterization of the atmosphere for modeling the relationship between the satellite data and the downwelling flux.

FLAT. The Full Look at Turbulent Kinetic Energy (FLAT) experiment, with investigators Steven Oncley (ASP postdoctoral fellow), Jim Wilczak (NOAA/Wave Propagation Laboratory, or WPL), Thomas Horst, John Wyngaard (MMM), and Alan Bedard (NOAA/WPL), was the first investigation of the turbulent kinetic energy (TKE) budget in the atmospheric surface layer in which all terms were measured directly. ASTER was used to measure the shear production, buoyant production/destruction, and turbulent transport terms using standard ASTER instrumentation. The TKE dissipation rate was measured using a hot-wire anemometer. Since dissipation occurs at very small scales, ASTER was configured to store the hot-wire data at 10,000 samples per second, an order of magnitude larger than the data rate specified for all of ASTER's standard sensors. The pressure transport term was measured by adding fast-response pressure sensors developed by NOAA/WPL. Other terms in the budget were expected to be negligible since the site, near Carpenter, Wyoming, is highly homogeneous in the horizontal (i.e., flat). ASTER collected data continuously during a ten-week period from September to November 1990, resulting in approximately 100 Gbytes of 10-kHz hot-wire measurements and 15 Gbytes of 1-Hz and 20-Hz data.

Nine PAM stations were deployed in a 3 x 3 grid surrounding the ASTER site to evaluate the assumption of horizontal homogeneity. One station was enhanced with radiation sensors to compare the albedo measured at the ASTER site with that of adjacent fields. Planetary boundary-layer (PBL) measurements were also included in FLAT. NOAA provided a 915-MHz wind profiler and an acoustic sounder. Mobile CLASS made several series of soundings at three sites separated by 25 km. Each triad of CLASS soundings was designed to measure horizontal temperature advection throughout the boundary layer. These measurements will also be used to study linkages between the surface layer and the PBL, to support a detailed one-dimensional model of PBL growth, and to scale the surface-layer data.

Hanna. Thirteen PAM-II remote stations were deployed near the Colorado-Wyoming border from 30 March to 14 April, to support a research program for Sigma Research Corporation (SRC) sponsored by both the U.S. Army and the U.S. Air Force, with Steven Hanna (SRC) as the PI. The objective of the program was to investigate the correlations of wind measurements on a mesoscale grid. The 13 PAM stations were deployed in an L-shaped array with two 10-km lines of 6 stations running north and west from a common station. The station spacing in each line was logarithmic and ranged from 312 m to 10 km.

HaRP. For the HaRP field program, SSSF deployed 50 PAM-II remote stations around the island of Hawaii with approximate spacings of 10 km. Stations were clustered on the windward side of the island and up the saddle (the area between Mauna Loa and Mauna Kea). Additional stations were more sparsely placed along the leeward side of the island. All stations in the network were configured to measure standard meteorological parameters (air temperature, pressure, specific humidity, horizontal wind, and rainfall). In addition, three stations on the saddle were enhanced to measure the radiation budget and soil temperatures. The PAM compact base station was installed at the HaRP data center located at the University of Hawaii in Hilo. HaRP was the first program to use the new PAM base computer in field operations. Previous projects used a DEC MicroVAX computer as the data acquisition and display system. For this program a Sun SPARCstation served this purpose. The Sun computer offered performance that was approximately an order of magnitude better than that of the MicroVAX. HaRP also provided an additional milestone: For the first time, Internet computer communications were available with the Boulder base station.

This project required a higher level of logistic support than any other PAM project in recent years. This was the first time that the PAM stations had to be sent off the U.S. mainland for deployment. The short time between funding of the project and its execution resulted in a number of station sites not being located until after deployment of the PAM stations was well under way. In addition, a number of stations were deployed in remote locations accessible only by four-wheel-drive vehicle.

Kanton Island. The Kanton Island Sounding System continues to support the TOGA community through the sponsorship of the NOAA TOGA Project Office. During the last year the station has achieved better than a 90% success rate on all sounding data. The Kanton system includes a surface meteorological station, an NCAR Omega sounding system, a remote power system including both wind and solar power sources, a battery power storage facility, and a custom modular building. The sounding system operates semiautomatically. The operator readies and releases the sonde, and then the data collection program operates automatically. The data are condensed and then transmitted via NOAA Geostationary Operational Environmental Satellite (GOES) to the meteorological community.

Providing logistical support to the Kanton Island station in a timely manner is still extremely difficult. In the past year some limited improvements have been implemented to the resident software. The first of these updates was delivered to the island through the cooperation of the Office of the Federal Coordinator for Meteorology and the New Zealand Air Force. The other update was delivered by the personnel of the New Zealand Calibration Flight when they were asked to do a runway inspection. These deliveries were separated by eight months and the changes fixed minor bugs and improved data quality.

Methane. A single PAM-II remote station was deployed in a cattle feedlot near Wellington, Colorado, for two weeks in March 1990. The station was installed to support an ACD project (Patrick Zimmerman, PI) designed to measure methane production and dispersion associated with cattle operations. As part of the experiment, ACD personnel released sulfur hexafluoride (SF_6) from the feedlot site and detected the gas downwind. The real-time display capability of PAM was used to control timing of the SF_6 release. PAM performance during the experiment was excellent.

Midwest Winter Cyclonic Storms. This program was a continuation of Robert Rauber's (University of Illinois) study of the mesoscale and microscale structure and evolution of precipitation bands and stratiform regions associated with wintertime continental storms. SSSF supported this research by providing a CLASS system to acquire local vertical thermodynamic and wind structure data to aid in the analysis and interpretation of other data sets collected during the study period. The CLASS system was based at Willard Field, Champaign, Illinois, during the period January-March 1990. Rauber's students made 125 upper-air soundings. The soundings started prior to the arrival of a storm and continued through its downrange passage. As in the research conducted during the previous winter, the sounding data were used to study the evolution of the thermodynamic profile of the atmosphere in relation to the onset and passage of the winter storms.

Nowcasting. During the summer of 1990 the mobile CLASS van and a Doppler radar from RSF were used together in a program studying localized storm cells throughout eastern Colorado. The CLASS van was directed by radio to a site and a sounding was made, often under very difficult conditions. The result of the sounding would determine if the van should be moved for another release or remain where it was. The surface sensors on the van were used to make interim measurements during the transit of the CLASS van between sounding locations. The data were used in near real time to advise aircraft of potentially hazardous storm cells in the area.

Air Pollutants. PAM support for Russell Dickerson's (University of Maryland) field studies continued until mid-November 1989, when the PAM-II remote station was removed. Because Dickerson's long-term requirements include multiyear monitoring of important atmospheric photochemical reactants that affect climate and air quality, SSSF staff provided technical assistance in the acquisition of a commercially manufactured meteorological station similar to PAM-II. SSSF staff also helped the vendor, Synergetics Corporation, to modify their station and duplicate the PAM data format to facilitate analysis with NCAR's ROBOT software used by Dickerson. Station intercomparisons were performed utilizing NCAR's GOES channels; however, the vendor experienced difficulties and has not yet completed its work. When Synergetics finishes the modifications, additional intercomparisons will be performed before hardware is delivered to Dickerson. ROBOT source code was given to Dickerson, and his personnelinstalled it on the University of Maryland computers. SSSF personnel are also helping Dickerson obtain an allocation on the GOES satellite data communications system.

Tropical Cyclone Motion-1990 (TCM-90). The TCM-90 field experiment was designed to measure the structure of typhoons in the western Pacific and adjacent synoptic features that govern their motion. Russell Elsberry (Naval Postgradute School), the TCM project coordinator, requested that two of the NCAR lightweight Loran digital dropwinsonde (L2D2) systems be installed in the NASA DC-8 to support this important study. Prior uses of L2D2 have been limited to propeller aircraft flying at altitudes up to 7,300 m (24,000 ft) and speeds of 130 m/s (250 kts). In TCM, the DC-8 flew at altitudes up to 12,500 m (41,000 ft) at speeds up to 250 m/s (490 kts). Numerous tests were successfully performed prior to TCM to ensure the reliability of the dropwinsonde parachute deployment system at these extreme altitudes and speeds. The interval between drops for a single L2D2 system on a DC-8 at high altitude was about 20 min, including 5 min for prelaunch preparations and 15 min for the drop. For TCM, a pair of L2D2 data systems were installed in the aircraft, allowing two sondes to be in the air simultaneously. This effectively halved the drop interval to 10 min in areas where increased spatial resolution was important.

The DC-8 operations for TCM were headquartered at Kadena Air Base, Okinawa, Japan, with ancillary operations from Andersen Air Force Base, Guam. The high point of the TCM missions was the three flights made on 16, 17, and 18 September into Supertyphoon Flo between Okinawa and Guam. Several penetrations to the eye of Flo were made and are believed to be the first ever for research aircraft at such high altitudes. A key question for these missions was whether Flo would curve rapidly in advance of a midlatitude trough or would drift northward more slowly, as predicted by various global models. The nearly 100 L2D2 data sets collected during these and other TCM flights will be intensively studied during the coming months to provide answers to this and other questions.

WISP-90. The Winter Icing and Storms Project utilized 19 PAM II remote stations and four CLASS systems along the Colorado Front Range during February and March 1990. The PAM stations were deployed in a variety of configurations. Fifteen had Rotronics thin film capacitance sensors added to provide humidity measurements below freezing, and seven sites were equipped with R.M. Young snow gauges. The Rotronic sensor performance was good for humidity, but the temperature accuracy was insufficient despite efforts to improve readings with enhanced aspiration and various air filters and radiation shields. The PAM dry bulb sensor remained the primary source for air temperature. Attempts were made to improve subfreezing psychrometer performance by using a 10% alcohol solution instead of straight distilled water. This proved ineffective because temperatures quickly dropped below the solution's freezing level, and using a higher alcohol content would have compromised accuracy. Snow gauge performance was variable, particularly as a consequence of the small catchment area of this new commercial sensor. Overall PAM data recovery was good, averaging 95%, although freezing and icing were problems for sensors, radios, and batteries on some occasions. A computerized database was used for the first time to help SSSF field technicians document station visits and sensor intercomparisons.

Approximately 300 soundings were taken from the four CLASS sites during WISP. Overall data quality and recovery were good. Freezing rain and icing of the ground-based equipment caused some degradation of data as well as missing soundings. In severe cases the hatches on the CLASS trailers froze shut, making balloon launches impossible. Ice on the ground antennas had a tendency to short out the received signal to ground, causing periods of poor reception.

It was noted during the project that wind data were often lost when radiosondes entered storm clouds. Atmospheric noise increased dramatically when this happened, causing poor Loran reception and consequently poor wind data. This phenomenon is well documented when releasing sondes in or near thunderstorms, but had not been as noticeable when operating in the winter in stratiform clouds.

Sensor and System Developments

ASTER. In FY 90 ASTER became an operational facility available to the scientific community. In February 1990, the ASTER facility was installed at the Marshall Field Site to conduct engineering and scientific evaluations. The system remained in operation until August 1990. The deployment at Marshall allowed for testing in a variety of environmental conditions ranging from cold winter storms to summer heat. During this time, a number of problems were corrected ranging from infrastructure modifications to software corrections. From an engineering perspective, system performance was quite good, with only minor problems. Scientifically, data evaluated for winds from an unobstructed fetch were satisfactory.

In September 1990, ASTER was deployed for the first time in Carpenter, Wyoming, to support the FLAT project. The system was deployed with no major problems, and operations continued until mid-November. A highlight during the FLAT project was the demonstrated flexibility with which ASTER was able to handle the requests made by the investigators. These included the extension of the standard 10-m towers to a height of 15 m, software development to handle two 10-kHz analog channels, and the integration of additional sensors into the system. ASTER also hosted visiting Soviet scientists who were comparing their flux instrumentation with that of ASTER.

The ASTER facility is capable of hosting user sensors. One type of sensor that is often used in the field of atmospheric chemistry has a modulated operation whereby the sensor continuously switches between different modes. As part of the ASTER development, SSSF has developed the interface for such programmable mode switching and has prepared an $NO/NO_x/NO_y$ sensor to operate with the ASTER facility during this year's field programs.

CLASS Upgrades. The nine NCAR CLASS systems recently received the first significant hardware upgrade since their construction in 1985. The upgrade centered on the electronic chassis that controls the flow of thermodynamic and Loran-C data into the system, and on the 400-MHz telemetry receiver. The new chassis is essentially the same as that previously developed for the L2D2 system. The new telemetry receiver is the same high-performance, digitally controlled unit SSSF developed for the L2D2 and Kanton Island sounding systems. It replaces a commercially produced receiver that is no longer manufactured or supported. Benefits realized from these improvements are increased depth of spares, easier maintenance, simplification of training for the field support staff, improved system performance, and commonality of system software.

SSSF has developed three CLASS systems for the National Severe Storms Laboratory and one CLASS/L2D2 system for the Canadian Atmospheric Environment Service for use in their research programs. These systems now benefit the atmospheric research community by providing additional equipment for field programs. Useful feedback on field applications has been received from both organizations and has been directly applied to the NCAR systems.

Conditional Sampler. An instrument to implement the conditional sampling technique (described under "Research and Technique Development," below) for measuring fluxes of nonreactive trace gases was built by Alan Hills (ACD) and Oncley. It has three valves to switch the flow into one of three sample bags corresponding to air in updraft, downdraft, and near-zero vertical wind regions. These valves are controlled by a microprocessor using data from a one-dimensional sonic anemometer near the sampler inlet. Some experience was gained by testing the sampler using a released SF_6 tracer, but the data were not sufficient to validate the use of this method for tracer fluxes. Definitive tests are planned for 1991.

Dropsonde. The L2D2 dropsondes remaining from the Experiment on Rapidly Intensifying Cyclones in the Atlantic (ERICA) were modified to resolve problems discovered during ERICA. A brass retainer clip was added to the sensor board, the transmitters were modified to allow for dual dropsonde operation, and the pressure sensors were baselined. The average pressure drift was found to be 0.7 mb relative to their initial calibration for ERICA. These modifications improved the reliability of the sonde, and expanded the capability of the L2D2 to allow operation of two sondes in the air simultaneously when there are two data systems installed on the aircraft.

In early 1990 SSSF proposed to the Air Force, through the Office of the Federal Coordinator for Meteorological Services, to modify and upgrade the L2D2 sonde for use with the Air Force Improved Weather Reconnaissance System. The major goals of this effort, which has now been funded, are to improve the L2D2 sonde, modify the navaid receiver so that it can be configured as either Loran or Omega, relayout the electronic circuit boards for surface mount components to increase the ease of manufacture, redesign the battery pack for easy replacement to solve a shelf-life problem, and increase the reliability of parachute deployment. The Omega version of L2D2 is the lightweight Omega digital dropsonde (LOD2).

A new parachute configuration has been designed for the LOD2. The pocket chute for L2D2 has been replaced by a square cone chute. The cone chute is immediately deployed upon release from the aircraft and is more slowly filled with air, eliminating some of the shock load on the dropsonde due to the sudden opening of the main chute. The new cone chute has been tested using NCAR's King Air and an Air Force C-130 with excellent results.

Enhanced GOES Telemetry. SSSF continues to manage the efforts of Cyberlink Corporation, which is supported by the Office of the Federal Coordinator for Meteorology, to study alternative communications techniques for environmental monitoring platforms using the GOES satellite. During FY 90, Cyberlink's final report on higher telemetry rates was presented to NCAR and the GOES user organizations funding these studies. The National Environmental Satellite Data and Information Service (NESDIS) subsequently approved use of an 8-phase-shift keying/Trellis coding method and set aside frequencies for ten 1200-BPS and ten 300-BPS channels. During 1990, code division multiple access (CDMA) was raised as another alternative data coding method. CDMA may offer reduced platform costs and expanded satellite access which would benefit the majority of GOES users more than high rate techniques, but it would be restricted to 100-BPS data rates as is the current scheme. Cyberlink's management summary and final CDMA report will be submitted in early 1991.

Infrared H_2O/CO_2 Sensor. Wim Kohsiek (visitor, Royal Netherlands Meteorological Institute, or KNMI, De Bilt) continued the development of a fast-response instrument to measure concentrations of both water vapor and CO_2 based on the differential absorption of infrared radiation. He was able to increase the accuracy of the instument to 0.06 g/m^3 in H_2O and 7 ppm in CO_2 by changing to a newer detector and optical fibers which utilize advanced technology. The H_2O response was reduced somewhat to optimize the sensor for CO_2. Data from deployment of this sensor during the FLAT experiment will be analyzed in 1991. Since the instrument performance is now acceptable, construction of a second instrument is planned for 1991 to allow ASTER to provide CO_2 flux measurements while development continues at KNMI.

Integrated Propeller Vane. An R.M. Young (Gill-type) propeller vane was modified for use in the ASTER facility wherein several sensors will be used for measuring wind profiles. The base of the sensor was completely redesigned for mounting on the ASTER towers. A 9-bit optical encoder was substituted for the standard direction potentiometer in the sensor. Electronics were added to the sensor to provide a calibrated serial data output. A Motorola 68HC11 microcontroller forms the core of the data acquisition electronics. The computer chip was programmed to allow entry of propeller pitch calibrations.

The sensor was tested in the NCAR calibration wind tunnel early this year. The tests indicated that the evaluation of sensor performance was limited by the inherent accuracy of the wind tunnel. Wind speed could be measured to better than 0.2 m/s. Better performance could be obtained by implementing a second-order polynomial calibration in the software, by using a higher-quality propeller, and by improving the wind tunnel facility used to calibrate the instrument.

Five wind sensors were deployed during the summer for field tests at Marshall with the ASTER system. During the fall, the sensors were deployed for the FLAT project. The sensors worked reliably except for one period during extreme freezing rain conditions, when water penetrated the seals and shorted the electronics of several units.

Integrated Sounding System (TOGA/COARE). During FY 90, SSSF and the NOAA Aeronomy Laboratory initiated Phase I of the development of a shipboard ISS. ISS is a suite of passive and active remote sensors and in situ surface and upper-air systems that will provide highly resolved profiles of winds, temperature, and humidity. The Phase I effort is for the development of a stabilization system for the UHF wind profiler antenna. The stabilization system consists of a gyro-stabilized platform that will remove the ship's pitch and roll, a set of three accelerometers for removing the ship's heave, and a satellite (GPS) navigation system to measure the ship's heading and speed.

A Phase II proposal has been submitted to the TOGA/COARE Project Office for support to complete the ISS development and to construct several shipboard and land-based systems for use during the TOGA/COARE Intensive Observing Period, which is scheduled for November 1992 through February 1993. The complete ISS system for COARE will consist of a UHF (915-MHz) wind profiler, a RASS for temperature, an Omega (navaid-based) upper-air sounding system, a surface meteorological measurement system, and a data system. The data system will process and correlate the data, provide on-site graphics capability, log the data, and generate standard meteorological messages for communication to the TOGA/COARE data center and the Global Telecommunications System (GTS).

The atmospheric profiles provided by these systems are necessary to complement and supplement existing and proposed surface and upper-air observations in the COARE domain, and to provide data that can be related to the larger spatial scales. These measurements are invaluable in documenting and understanding westerly wind bursts, since the various objective analysis schemes do not accurately define winds in regions of limited observations. Accurate profiles of winds and atmospheric state variables in the equatorial western Pacific are also critical for understanding oceanic responses, a crucial element of the TOGA/COARE program.

Mobile CLASS. A mobile CLASS facility was developed in response to a need of the scientific community for a sounding system that can be easily and quickly moved from place to place. At the core of the mobile system is a semistandard CLASS system that has been modified and installed in a standard nine-passenger van. The operators drive the van to a specified launch site, set up the surface system (providing wind speed and direction, temperature, and humidity), set up the upper-air system, and then release a balloon-borne radiosonde and initiate a sounding. During the sounding the operators may drive the system to the next location for a later release, while continuing to receive and record sonde data. The mobility of this system opens up a number of unique opportunities for meteorological research.

To date the mobile CLASS system has participated in several important research projects. The nowcasting project in eastern Colorado was the inaugural project for mobile CLASS (see "Nowcasting," above). During the fall of 1990 the system was used in Wyoming supporting project FLAT. In this case soundings were made at three corners of a box approximately 15 km square. The requirement was to make these soundings as fast as possible and move to the next location and repeat the process. A complete circuit was completed in approximately 90 minutes. The system will also support the WISP-91 project during the winter of 1991 and the CAPE project during the summer of 1991. In each case, the mobility of the system and the versatility afforded the PI were the basic reasons for the request of the mobile CLASS system. This system has proven to be both easy to use and reliable while providing excellent data sets.

Pressure Sensor Development. Since the development of PAM-I, engineers in SSSF have improved the measurement of pressure at PAM remote stations. Over the last three years, work has centered around a silicon diaphragm transducer having negligible hysteresis, repeatable characteristics, and low cost. This type of pressure transducer was used as part of the L2D2 dropsonde development. Since factory calibrations were not adequate for meteorological applications, individual sensors were calibrated over the temperature and pressure ranges the dropsonde would experience. The pressure range was 150 to 1050 mb, and the temperature range was 0° to 30°C. Using computed coefficients, the average errors were typically 0.5 mb, with standard deviations less than 1 mb. A test was done in August 1990 to determine long-term drift characteristics. One hundred seventy-four sondes, which had been calibrated 20 months earlier, had an average difference error of 0.74 mb with a standard deviation of 0.6 mb, in comparison with a reference standard.

The new pressure transducer is also being incorporated into the PAM-II surface meteorological system. Two prototype boards are now in a testing mode. The boards have gone through preliminary tests in the calibration lab. Plans are to start field testing in FY 91. Desired goals are an absolute accuracy of 0.3 mb over a pressure range of 600 to 1050 mb and a temperature range of –30° to 50°C.

Research and Technique Development

Conditional Sampling Technique. In order to measure the vertical fluxes of chemical species for which instrument response is too slow for the eddy-correlation technique, a conditional sampling method was proposed by Joost Businger and Oncley in the *Journal of Atmospheric and Oceanic Technology*. This method involves collecting two time-integrated samples of the chemical species, segregated by the sign of the vertical velocity component, and assuming that the flux is proportional to the product of the standard deviation of the vertical velocity and the chemical concentration difference between the two samples. Businger and Oncley found from simulations with existing time series data that the coefficient of proportionality, b, is almost constant over a wide range of atmospheric stability. Businger has subsequently developed an explanation of the lack of dependence of b on stability, based on surface-layer similarity theory. At the same time, Horst, Chin-Hoh Moeng (MMM), and Wyngaard have predicted b from the joint probability density between the chemical scalar and vertical velocity. Assuming a joint normal probability density, predictions of the latter approach of the magnitude of b and its dependence on a vertical velocity measurement threshold are similar to those from the simulations of Businger and Oncley.

The conditional sampling technique as originally conceived is appropriate for atmospheric species that are relatively inert and that can tolerate storage without significant chemical degradation. Anthony Delany has investigated different options whereby the fluxes of more reactive species can also be investigated. The techniques considered will allow the concept of conditional sampling to be extended to reactive species that cannot be subjected to storage but for which relatively slow sensors exist. Ozone is the first trace gas to be tested. A further series of tests will consider atmospheric aerosols. This work is being carried out in conjunction with NOAA scientists.

Flux Footprint Modeling. A flux footprint relates the vertical flux measured at some height above the surface to the distribution of surface emission fluxes. Horst has calculated this footprint from an analytic diffusion model for ground-level sources. This approach leads to a nondimensional footprint function that allows application of a single curve to a broad range of field measurement situations, and allows the use of existing surface-source tracer-experiment data for footprint estimation. In order to remove some of the simplifying assumptions of the analytic model, Jeffrey Weil (MMM long-term visitor) and Monique Leclerc (University of Quebec at Montreal) have collaborated by providing Lagrangian stochastic diffusion model calculations to compare with those of the analytic model. These results were presented at the Seventh AMS Symposium on Meteorological Observations and Instrumentation.

Orographic Boundary-Layer Circulations. Observations from the 1985 South Central Coast Cooperative Aerometric Monitoring Program (SCCCAMP) field program in the California Santa Barbara Channel provided details of a variety of flow features: mesoscale vortices, land/sea breezes, and slope flows. Wilczak, Walter Dabberdt, and Robert Kropfli (NOAA) have investigated the structure of the so-called midchannel eddy using observations and mixed-layer model simulations, and have shown that the eddy depends on stratification and interaction of drainage flows with the large-scale flow. Their results have been accepted for publication in the *Journal of Applied Meteorology.*

PAM Pressure Port Response. Wind tunnel measurements of the pressure errors induced by the PAM pressure port have been made at the University of Missouri-Columbia by Henry Liu and Adnan Akyuz. Based on these measurements, standard micrometeorological knowledge, and climatological wind speed distributions, Horst completed an analysis of the expected error in PAM pressure measurements as a function of the mean and variance of the elevation angle of the wind. The analysis showed that the pressure port errors were generally smaller than the root mean square error in the pressure transducers. A joint paper has been accepted for publication in the *Journal of Atmospheric and Oceanic Technology.*

Sensor Performance. Vincent Lally, Kenneth Norris, and Steven Semmer have continued their evaluation of the performance of dropsonde pressure and humidity sensors. The pressure sensor has been tested under dynamic temperature changes typical of a drop profile. The pressure sensor has a 1- to 2-mb error under rapid temperature changes. Further evaluation of solid-state pressure sensors and the associated electronics is currently under way with the goal of improving pressure sensor performance. A commercial company has produced a new hygristor that shows promise for dropsonde applications. This sensor consists of a heated element on an alumina substrate (alumina has high thermal conductivity and is a nonconductor electrically). The sensor has a humidity-sensitive coating on one-half of the top surface and a thermistor coating on the other half. The wafer is heated by a printed circuit resistor on the bottom surface.

Urban Dispersion. Dabberdt has continued his research into problems of urban dispersion in collaboration with the wind tunnel modeling facilities of Walter Hoydysh (ESSCO). Tracer dispersion experiments were performed in an atmospheric boundary-layer wind tunnel to study street-canyon dispersion and its sensitivity to block shape and entrainment from adjacent blocks. Phenomenolgical results from this systematic study are to appear in *Atmospheric Environment*, along with a new modeling approach. The new model recognizes the roles of two flow regimes—vortex formation and purging—and draws on puff-type diffusion to explain the negative concentration gradient typically observed on both the windward and leeward sides of urban street canyons.

Remote Sensing Facility

Mission and Goals

The mission of the Remote Sensing Facility (RSF) is to provide state-of-the-art Doppler weather radars and radar data analysis software in support of atmospheric sciences research. In meeting its mission requirements, RSF engages in the following major activities:

- development and field operation of Doppler weather radar systems in support of atmospheric sciences research
- support of users of RSF facilities through consultation on field project design and implementation, and data analysis and interpretation
- development and operation of interactive computing capabilities, display systems, and software for these interactive computers, in support of scientists who use these systems
- development of operational and analytical techniques for optimal use of RSF facilities, and transfer of these techniques to the atmospheric sciences community
- scientific research in topics related to RSF- and ATD-supported activities
- collaboration with university and NCAR scientists and engineers in developing needed new facilities.

RSF's goals are to provide the best possible support to users in all approved field projects, to improve facility capabilities, and to develop new facilities in the most needed areas.RSF support activities in FY 90 have primarily focused on studies of winter storms and aviation icing, subtropical rainband formation, microburst observation and warning, forecasting techniques, and initiation of convection. Development activities within RSF have been directed toward airborne Doppler radar, new generation radar processors, and upgrades to RSF C-band radars and the Mile High Radar. In addition, RSF staff have participated heavily in planning for mesoscale and subsynoptic-scale research programs, including STORM and TOGA/COARE.

Radars and Capabilities

RSF operates four Doppler weather radars in support of atmospheric sciences research. These are described below.

CP-3 and CP-4. The CP-3 and CP-4 C-band Doppler radars are a pair of highly transportable, fully coherent Doppler radars. They have a peak transmitted power of about 1 MW, 1° beamwidths, an antenna gain of 44 dB, and scan rates of up to 20°/s. One of the C-band antenna systems can be configured in the future to include polarization diversity measurements. During FY 90, the new RP-7 radar signal processor was implemented on both C-band radars. Recently completed upgrades to the radars include new antennas with 44 dB gain and -26 dB first sidelobes, improved antenna drivers, new antenna scan controllers, and the new radar processor. These are the radars of choice for field projects not requiring S-band capabilities or in-depth cloud microphysical measurements as are provided by the CP-2 radar.

CP-2. The CP-2 radar is a highly sophisticated Doppler radar with a dual polarization vertical and horizontal Doppler S-band radar and an incoherent X-band radar. The latter has a single polarization feed antenna and dual vertical and horizontal polarization receiver antennas, thus giving measurements of X-band linear depolarization ratio. Although the CP-2 is one of the most sophisticated cloud physics radar in the world, it was out of service during FY 90 because of funding shortfalls. RSF staff maintained the radar in a state of protected storage during FY 90 and are working with CaPE researchers to bring the radar back into operation in FY 91.

Mile High Radar. The Mile High Radar (MHR) is a modern Doppler radar built by Raytheon as its candidate for the NEXRAD competition. It is sited 22 miles northeast of Denver's Stapleton International Airport. Under contract from the FAA and the National Weather Service, RSF runs the MHR on an operational basis to provide real-time weather warnings for Stapleton International Airport and the NWS. Data from MHR are fully available to the scientific research community on a noninterference basis. During FY 90, weather warning data from MHR were credited with providing microburst warnings that saved at least one aircraft from crashing at Stapleton International Airport, and also with providing a critical 10-min warning that prevented loss of life or serious injury when a tornado destroyed the town of Limon, Colorado.

Field Support Activities

RSF's field support activities in FY 90 are listed in Table 3 and summarized below.

Table 3. RSF FY 90 Support Activities.

Project	Scientist	Topic	Location	Dates
HaRP	Mitch Moncrieff et al.	Rainband formation	Hilo, Hawaii	16 July–23 August
Nowcasting	James Wilson et al.	Development of short period forecasting techniques	NE Colorado	1 June–31 July
WISP	Cathy Kessinger et al.	Winter icing	Colorado Front Range	15 January–31 March

WISP. The 1990 field phase was the first of two consecutive winter field campaigns. The MHR and CP-3 Doppler radars, instrumented research aircraft, CLASS, PAM, radiometers, and wind profilers were involved. This was the first program in which RP-7 was used on the RSF C-band radars. As a result there were some biases in the Doppler velocities and some uncertainties about ground clutter filter effects. However, these errors did not significantly affect the WISP dual-Doppler analyses, since their purpose is to examine larger-scale kinematic features. Data from both RSF radars were sent in real time to an operations center in Boulder. This made it possible, for the first time, to generate dual-Doppler wind fields in real time.

HaRP. Model predictions of the three-dimensional airflow around the island of Hawaii played an important role in formulating the overall design of the experiment and in providing specific guidance on the placement of RSF's C-band Doppler radars (CP-3 and CP-4), as well as the 50 PAM stations. In combination with the Electra research aircraft, these systems were able to collect an extensive data set illuminating many aspects of the physical properties and dynamic structure of the rainbands. This data set will be used by NCAR and university scientists to gain a better understanding of the complex interactions between the trade winds and the island, as well as a better understanding of tropical clouds and precipitation.

Nowcasting/Mile High Radar. The MHR was the key radar for the nowcasting research project led by Wilson. This project is part of an ongoing effort by RAP, ATD, and MMM to develop very short-range forecasting techniques for aviation purposes. The forecast region is in northeastern Colorado, including the Denver metropolitan area. Forecasters used the radar and other data in real time to test and evaluate new storm forecasting techniques.

The MHR supported a multitude of other users during FY 90. MHR data were combined with other data sources at NOAA's Forecast Systems Laboratory and transmitted to the Denver NWS forecast office for forecasting and technique development. Likewise, MHR data were processed at NCAR's Research Applications Program and sent to the Denver control tower and Longmont air traffic control center to develop various aviation hazard warnings. The utilization concepts for the NWS WSR-88D Doppler radar network and the FAA Terminal Doppler Weather Radar (TDWR) installations were refined through the use of MHR data. The radar also supplied information for operational issuance of actual weather and aviation forecasts for the Denver area.

The MHR operated daily for the FAA and NWS during the convective season (1 May through 31 August). Operations for winter precipitation events were on an on-call basis; the NWS and WISP operations center gave MHR staff a 12-h notification after completing their daily outlook. System modification and testing were accomplished during an autumn down-time period and on fair weather days. Reflectivity factor, velocity, and spectrum width estimates were made available to the sponsor's laboratories in real time, were recorded continuously on tape at the MHR site, and were archived by RDP for postanalysis.

Development Activities

C-Band Upgrades. A multiyear program of upgrades to the NCAR C-band radars began in FY 90. One major upgrade was the installation of antennas on both C-band radars. These new Ericsson 4.2-m antennas are a considerable improvement over the previous antennas; they provide 44 dB gain and about -26 dB first sidelobes. The pedestals and trailers were reinforced to accommodate the new larger, heavier antennas, and the trailers and equipment were repackaged. A handling system was designed to the new antennas. Preliminary pattern tests were performed to characterize the antennas. In addition, a digital servo control loop was designed and built to precisely control the antennas. Other improvements to these radars included:

- installation of the RP-7 radar processor and development of a new radar display capability
- development of expanded dynamic range dual-channel receivers
- modifications to the radar systems to lower radio frequency noise to enhance dynamic range
- development of software tools to allow manual removal of receiver DC drift, and to provide a real- time FFT display capability to aid in receiver tuneup
- improvements to facilitate overseas (tropical) transportation and operation
- design, fabrication, and implementation of circuits that eliminate the 5-cm portion of the receiver coherent leakage during the normal radar receive time.

These changes improve the serviceability and reliability of the radars and provide for future upgrade opportunities. With these improvements installed, the C-band radars performed excellently during HaRP. This C-band upgrade program will extend into FY 91, and will include renovation of the radar data system as well as replacement of additional aging radar components. New data-processing and display capabilities will be also added.

ELDORA. The final details of the U.S.-French International Agreement for the joint construction and use of the Electra Doppler radar (ELDORA) were completed in FY 90 at an in-depth technical meeting that was held in Paris, and chaired by Peter Hildebrand from RSF and Jacques Testud from the Center for Research in the Physics of the Terrestrial and Planetary Environment (CRPE, Issy-les-Moulineaux, France). The agreement, which was signed in Paris in January 1990, states that NCAR will provide the major radar components, the modified aircraft, and much of the operational and analysis software, and that CRPE will provide the rotodome and antennas, some receiver components, and additional analysis software. The agreement provides for a proportionate level of access by the U.S. and French scientific communities to the completed system. Since the signing of the NCAR/CRPE agreement, regular quarterly meetings have been held in the United States and France, and the development has continued on schedule.

Significant progress was made during FY 90 in the development of all major radar components. The ELDORA Testbed Radar was brought into operation in the laboratory, and operation of this prototype radar system strongly enhanced ELDORA development activity in many areas:

- the radar data display card was selected and the range-height indicator (RHI) display designed
- the control bus was specified, a proof of concept was performed, and the generic master and slave interfaces were designed
- the program to control the radar, based on scientific input, was written and is being tested and improved

- templates of the rotodome/aircraft interface were designed and construction was begun, and research was done on navigation equipment to be used in the rotodome

- the radar transmitter progressed from design to construction

- the signal synthesis system passed through breadboard testing to design of the final components

- testing of the RP-7 radar processor was accomplished

- design criteria for the final form of the ELDORA radar processor were completed.

At the same time, data display software was developed to display output from the ELDORA Testbed Radar in real time. Additional radar development efforts included tests of recording media and initiation of radar control software development.

The request for proposal (RFP) for airframe modifications to the Electra was written and solicited to industry in FY 90. Because of funding shortfalls, this contract had not yet been awarded at the end of the fiscal year. Final selection of the modification contractor is expected in early FY 91.

During FY 90, the ELDORA staff assisted RAF with the purchase of new inertial navigational equipment. In addition, the ELDORA staff oversaw the contract for the high power amplifiers being constructed at Quarterwave Corporation, and they also designed and built the high power amplifier controller.

Mile High Radar. Since its installation in 1989, the MHR has undergone a substantial number of modifications to improve its performance and reliability. The FY 90 modifications are as follows:

- antenna system
  - the azimuth drive train and waveguide were replaced
  - the Daytron motion controller was modified
  - optical motor encoders were added.

- transmitter
  - wiring harnesses were refurbished
  - module connectors and alignment mechanisms were replaced
  - the digital controller fault detection was modified
  - the intermediate power amplifier and RF modulator were replaced.

- processing subsystem
  - the signal processor was replaced with the first dual-channel RP-7
  - the data/control processor was replaced with a VME 68030
  - the radar timing generator was replaced
  - a selection of 15 clutter filters was added
  - the DSP and host software was upgraded
  - postprocessing capability was added
  - time series mode was added
  - an X-window operator control panel with autoscan and manual modes was added.

- communications and archiving
  - base data recording capability on 8-mm cartridge tapes was added
  - the point-to-point base data transmission with Ethernet multicast in standard radar format was added.

These renovations were completed primarily during the winter season, and the radar was ready on schedule for the summer field operations.

RP-7. During FY 90, the new RP-7 programmable radar signal processor[1] was installed on both RSF C-band radars, the MHR, and the ELDORA Testbed Radar, and it was brought into its first full operation. This installation provided good data from all four radars. The C-band radars, with RP-7 installed, supported the HaRP and WISP projects and provided a large and unique new data set. The RP-7 on MHR provided reliable data which were used in all data analysis functions for the radar, and the RP-7 on the ELDORA Testbed Radar provided the needed flexibility of operation for initial testing of some ELDORA transmission concepts. New features on the processor include ground clutter suppression and the ability to revise the processing algorithms nondestructively. Currently the pulse pair algorithm is used to estimate spectral moments. Frank Pratte, Charles Frush, and Jeff Keeler are investigating new clutter filtering and pulse compression techniques for more robust exploitation of the data. The base data are output on Ethernet for local display and transmitted to a remote operations center. Joseph VanAndel is developing diagnostic routines for plotting the digitized data, for the spectral plots of the sampled data, and for the "A-scope" displays of the processed base data that are being recorded.

University Interactions

During FY 90, RSF had a considerable amount of university interaction. During HaRP, Dave Johnson (scientific visitor) set up the Project Office and Data Analysis Center on the campus of the University of Hawaii at Hilo (UHH). While at UHH, RSF worked closely with the Department of Computer Science (George Koide, chairman) and provided summer support for an undergraduate student in the department (Normand Dionne).

Wen Chau Lee (visitor, University of California, Los Angeles) worked with David Chen (University of Hawaii at Manoa) on testing custom editing and display software. In addition, Lee presented a seminar on the evolution and structure of the bow echo/microburst event to the Department of Atmospheric Science at Taiwan's National Central University and National Taiwan University (NTU). Lee also taught a three-day class on Doppler radar data analysis at NTU.

Keeler was an adjunct professor at Colorado State University (CSU) where he assisted in teaching meteorological radar courses and served on several thesis committees. Keeler also was a member of the CHILL Radar Advisory Committee at CSU. Keeler worked with the National Central University in Taiwan to investigate the potential of converting their WSR-68 weather radar to a Doppler radar.

Hildebrand made the following university contacts in FY 90: Larry Mahrt, Oklahoma State University (Hydrological Atmospheric Pilot Experiment data); Moti Segal, CSU (research); Roger Wakimoto, University of California, Los Angeles (HaRP planning); Alan Bandy, Drexel University (Electra use

[1] A programmable processor based on the ATT DSP32C digital signal processing (DSP) chip.

planning); Steve Rutledge, CSU (radar use planning and TOGA/COARE); Viswanathan Bringi, CSU (HaRP planning, TOGA/COARE planning, and university interactions); Ramesh Srivastava, University of Chicago (RSF planning and WISP); Roscoe Braham, University of Chicago (RSF planning); and David Atlas, University of Virginia (RSF planning).

Frush worked with Bob McIntosh (University of Massachusetts) regarding his work in very short wavelength Doppler radar. Frush also worked with the CHILL radar staff at CSU regarding logistics, installation, and research on bandpass-limiting intermediate frequency (IF) signal processor performance.

Education and Training

Keeler participated in the Taiwan Central Weather Bureau (CWB) Atmospheric Instrumentation Workshop in March 1990. He presented a series of lectures on principles of Doppler radar to CWB, the Civil Aviation Agency, the Chinese Air Force and Navy, and the university community. Keeler also advised the Alaska National Weather Service in Anchorage on performance of volcanic-plume-tracking radar.

During HaRP, the University of Hawaii at Hilo conducted its Student Science Training Program (SSTP), bringing together outstanding high school students from throughout the United States as well as from a number of foreign countries. Johnson (the RSF HaRP project manager) coordinated a series of tours of project facilities for the SSTP students, arranged for several HaRP investigators to work individually with SSTP students on independent research projects, and presented a lecture describing the project and its scientific rationale.

Johnson, James Ziese, and Brian Lewis attended a meeting of the Big Island Radio Club in Hawaii and made a presentation about the HaRP project. They gave an overview of the project with particular reference to the RSF C-band Doppler radars and project requirements for radio communication links. Johnson also served as co-chairman of the Session on Orographic Clouds at the 1990 AMS Conference on Cloud Physics (San Francisco, 23–27 July 1990).

In the summer of 1990, RSF hosted Patricia Cabrera, a student from the University of California, Irvine. Patricia was a participant in NCAR's summer student program, and she worked primarily with the ELDORA group.

RSF Staff Research Activities

Hildebrand. During FY 90, Hildebrand collaborated with Testud (visitor, CRPE), to study the effect of aircraft radar pointing angle alignment on the data collected by the radar. Their analysis provides a new technique for determination of and correction for errors in mounting the aircraft radar antenna. Hildebrand also completed two boundary-layer studies during the year, including revisions of a joint paper with Segal et al. on the snow boundaries experiment. He also completed revisions of a chapter in a book on airborne flux measurement techniques and measurement accuracy. In addition, Hildebrand presented a paper on aircraft weather avoidance radar at the International Civil Aviation Organization meeting in Montreal, Canada.

Keeler. Keeler and Frush have continued exploratory research on a new rapid scan Doppler weather radar. Plans have been made to install an improved antenna on the X-band Doppler ELDORA Testbed

Radar in 1991 and to generate various pulse compression waveforms. These test data will be recorded and processed in real time to show the applicability of wide-bandwidth waveforms on distributed weather targets. The short dwell time waveforms used with an electronically scanned beam are expected to allow Doppler measurements of the atmosphere to be made an order of magnitude faster than possible with today's conventional Doppler radars.

Johnson. Johnson's primary research interests are centered on the physics of tropical clouds and precipitation, with particular reference to the data set collected during HaRP. His major studies concern the radar reflectivity structure and diurnal evolution of the rainbands. He is also involved in the acquisition of high-resolution meteorological satellite data for mesoscale studies of the airflow and updraft structure around the island. In a related effort, he is investigating the cloud droplet concentrations found in maritime clouds upwind of the island chain.

Frush. Frush has continued his investigations in the area of remote sensing of trace gases—especially CO_2, H_2O, carbon monoxide, ozone, and methane. He is identifying opportunities that NCAR might pursue in order to bring these measurement capabilities to the scientific community.

Frush has also done preliminary research on developing an instrument for rapidly measuring the liquid water content of a volume of air in the immediate vicinity of an airborne measurement platform. The method investigated involves measuring the increase in electrical length between two microwave antennas (horns) caused by the increased bulk dielectric constant of a volume containing water droplets. An apparatus was constructed that could measure changes in electrical length in a 3-m path to a precision of about 1 part in 10^5.

Wilson. Wilson and Rita Roberts (RAP) have been studying the formation of three nonsupercell tornadoes that occurred near Denver on 15 June 1988 within the range of two Doppler radars. They are conducting the study to examine the hypothesis that nonsupercell tornadoes develop when small vortices, produced by shearing instabilities along a surface convergence boundary, become stretched in the updrafts of developing thunderstorms and eventually intensify to tornadic intensity. Wilson also worked on an experiment in Darwin, Australia, that was based on detection of boundary-layer convergence lines by Doppler radar. Wilson and his co-workers completed a paper that demonstrated the role of boundary-layer convergence zones and horizontal convective rolls in the initiation of thunderstorms. In addition, Wilson worked on the Denver Summer Nowcasting Evaluation, which consisted of research and development of forecast models and the testing of these models during summer forecasting experiments. During the summer of 1990, Wilson and other NCAR meteorologists prepared 30-min forecasts that were displayed at the Stapleton control tower and at the air traffic control center.

Lee. Lee worked with Richard Carbone and Frank Marks (NOAA) on the "velocity track display" technique, a method to derive primary hurricane circulation in real time using P-3 tail Doppler radar data. Lee helped plan and attended the HaRP field project and also worked with Cathy Kessinger (RAP) on real-time dual-Doppler radar display during the WISP-90 project.

Research Data Program

Mission and Goals

The Research Data Program (RDP) supports the scientific user community and the ATD facilities via service and development in each of the following areas:

- data archival, access and distribution—through development and maintenance of a comprehensive data archive providing for access to integrated multiplatform ATD data sets, timely distribution of these data via appropriate media, and associated data access software

- analysis software tools—through development, maintenance, and user support of advanced software tools for editing, display, overlay, scientific processing, and analysis of ATD and other data sets

- real-time field project control—through prototype development and user support for a transportable field control center providing state-of-the-art facilities for data display and assimilation, field communications, nowcasting, forecasting, and facility control. Efforts include examination of prototype systems supporting field-phase scientific analysis by field project participants

- networking and distributed computing—through coordination of distributed computing development within ATD to maximize connectivity and compatibility among ATD facilities and users within and outside of NCAR.

Data Management

RDP serves as a "one-stop" source for ATD data sets, associated documentation, and consulting services related to data access and analysis software. Data distributed through RDP in FY 90 included aircraft (Sabreliner, Electra, and King Air), radar (CP-2, CP-3, CP-4, and Mile High Radar), and PAM measurements. Data handling will expand in FY 91 to include CLASS and ASTER measurements.

FY 90 saw increased reliance on NCAR's Mass Storage System (MSS) as a central data archival system. Virtually all data sets handled by RDP are archived on the MSS, and a growing number of requests for small data sets (tens of MBytes or less) are satisfied through network transfer directly from the MSS to the user. FY 90 experience has shown this mode of data service to be highly effective in meeting community needs for distribution of smaller data sets. Further development and use of network transfer techniques are planned for FY 91.

Data distribution via physical media was accomplished through conventional 9-track tapes, PC floppy disks, and high-density 8-mm cassettes utilizing advanced Exabyte data recording technology. Favorable experience with the relatively low-cost, high-capacity Exabyte medium indicates that this technology is likely to play a significant role in short-term archival and data distribution activities over the next several years. Examination of DAT (digital audio tape) recording technology continued in FY 90, but DAT will not be utilized by RDP until recording industry standards are established. Data distribution via floppy disk continues to be a very low-volume activity related only to the special needs of a few users. As shown in Table 4, 45 non-NCAR researchers requested and received data management support from RDP in FY

90. Additional data management support was provided to NCAR researchers in MMM, ACD, ASP, RAP, and ATD.

Table 4. Non-NCAR Researchers Receiving Data Distributions From RDP in FY 90.

Name	Affiliation	Data Type	Project
Nolan Atkins	UCLA	Radar	(misc)
Roger Brown	NSSL	Radar	North Dakota Thunderstorm Project (NDTP)
Steven Campbell	MIT Lincoln Lab	Radar	(misc)
Joe Chang	Sigma Research, MA	PAM	Hanna
Steven Chiswell	N Carolina State U	Radar	(misc)
Waylon Collins	UCLA	Radar	Convective Initiation and Dowburst Experiment (CINDE)
John Conway	Univ of Oklahoma	Radar	May Polarization Experiment
Russell Dickerson	Univ of Maryland	Aircft	(misc)
Michael Dixon	Univ of Colorado	Radar	Program for Regional Observing and Forecasting Services (PROFS)
Bruce Doddridge	Univ of Maryland	PAM	SMOG
Gregory Forbes Project	Penn State Univ	Radar	Microburst and Severe Thunderstorm (MIST)
Carl Friehe	UCLA	Aircft	Shelf Mixed Layer Experiment
Chester Gardner	Univ of Illinois	Aircft	Sodium Lidar
Robert Grossman	Univ of Colorado	Aircft	Convective Waves
John Hallet	DRI, Nevada	Aircft	Sci. Training
Paul Heberling	General Electric	Aircft	Nelson
Mark Hjelmfelt	SDSMT	Radar	NDTP
Arlen Huggins	DRI, Nevada	Radar	UTAH85
Warawut Khantiyanan	SDSMT	Radar	MIST
David Kingsmill	UCLA	Radar	MIST
Abby Lindstrom	Univ of Maryland	Aircft	Convective Waves
Thomas Matejka	NOAA	Radar	PRESTORM
Donald May	Colorado State Univ	PAM	(misc)
Raymond McAnelly	Colorado State Univ	Radar	CINDE, WISP90
Sankaran Menon	Colorado State Univ	Radar	MIST
R. Niciejewski	Univ of Michigan	Aircft	Sodium Lidar
Richard Pearson	NASA	Aircft	Central Pacific Air Chemistry Experiment
David Priegnitz	SDSMT	Radar	NDTP
Ronald Rinehart	Univ of North Dakota	Radar	NDTP
Alfred Riordan	N Carolina State U	Radar	Genesis of Atlantic Lows Experiment (GALE)
William Roberts	NOAA	Radar	GALE

Name	Affiliation	Data Type	Project
Brian Robins	Univ of Colorado	PAM	Joint Airport Weather Study (JAWS)
Robert Shedd	NWS/NOAA	Radar	PROFS, CINDE
Ramesh Srivastava	Univ of Chicago	PAM	JAWS
Daniel Taylor	Baruch Univ	PAM	Baruch
Ali Tokay	Univ of Illinois	PAM	HaRP
Steven Vasiloff	NSSL	Radar	NEXRAD
J. Vivekanandan	Colorado State Univ	Radar	CINDE, misc
James Wilczak	NOAA	Radar	PROFS, other
Patrick Wright	NASA/Huntsville	Radar	MIST
JengHwa Yee	Univ of Michigan	Aircft	Sodium Lidar
Dia Yiu	Univ of Toronto	PAM	JAWS
Edward Zipser	Texas A&M Univ	Aircft	Equatorial Mesoscale Experiment

Data Analysis Support

The Research Data Support System (RDSS) serves as a user-oriented data analysis facility and a development center for data display and analysis software. RDP scientific and programming staff provide consultation and support to community scientists making use of RDSS analysis tools, which support the perusal and editing of radar data, display of PAM data, and editing and display of CLASS and other sounding data. Development and acquisition of tools for aircraft data analysis are planned for FY 91.

The RDSS computing system includes a SUN-4/280 computer, two SUN-3/60 diskless workstations, several SUN SLC diskless workstations, two Ardent Titan graphics workstations, and a VAX 11/780. Multiple tape drives (9-track and Exabyte) and large disk storage capacity available to the scientific user provide for flexible ingest and manipulation of large data sets.

FY 90 users of the RDSS facility are shown in Table 5. Intensive use of the facilities by ten university investigators outside of the Boulder area was accomplished by visits to RDP for periods of two days or longer during which RDP staff provided consultation. Other remote users accessed the system via dial-up lines or Internet.

Table 5. Users of the Research Data Support System in FY 90.

V.N. Bringi	CSU
David Blanchard	NOAA/WRP
V. Chandrasekhar	CSU
Yi-Leng Chen*	University of Hawaii
Thomas Christian	NOAA Atmospheric Studies
Waylon Collins	UCLA
Peter Coppin	Commonwealth Scientific and Industrial Research Organization, Australia
Phillip Currier	NOAA Aeronomy Laboratory
Robert Dattore	CSU
Russell Dickerson	University of Maryland

Clive Dorman	Scripps Institute of Oceanography
David Fitzjarrald	State University of New York
Gregory Forbes*	Pennsylvania State University
Carl Friehe	Univ of California, Irvine
Bob Grossman	University of Colorado
Michael Hardesty	NOAA/WPL
Mark Hjelmfelt*	South Dakota School of Mines and Technology
Robert Hood	NASA/MSFC
Anthony Illingworth	University of Manchester Institute of Science and Technology, England
Janet Intrieri	NOAA/WPL
Richard Johnson	Colorado State University
Kevin Knupp*	Univ of Alabama
Brian Klimowsky*	University of Wyoming
Kevin Knupp	University of Alabama
Robert Kropfli	NOAA/WPL
Frank Lin*	St. Louis University
John Marwitz*	University of Wyoming
Don May	Colorado State University
Raymond McAnelly	Colorado State University
Rebecca Meitin	NOAA/WRP
Jose Meitin	NOAA/WRP
Bill Michener	Baruch Institute
Jeff Pedigo	NOAA Forecast Systems Lab
David Priegnitz*	SDSMT
Ron Rinehart	University of North Dakota
Alfred Riordan*	North Carolina State Univ
William Roberts	University of Colorado
Tim Schneider	NOAA/WPL
Boba Stankov	NOAA/WPL
Gabor Vali	University of Wyoming
J. Vivekanandan*	Colorado State University
Sue Lee Wang	NOAA/NSSL
James Wilczak	NOAA/Environmental Research Lab
Daniel Wolfe	NOAA/WPL
Patrick Wright	NASA/MSFC
Staff of ATD, MMM, CGD, SCD, RAP	NCAR

* Visitors to RDP

RDSS analysis tools are developed and maintained to facilitate portability to users' home computing facilities. While many users visited RDP to use these tools in FY 90, implementation of RDSS tools at users' institutions also increased in FY 90, as shown in Table 6. The full breadth of distribution of RDSS analysis tools to date is shown in Table 7.

Table 6. Software Distributions in FY 90.

Radar Perusal and Editor	Bob Rauber (Univ. of Ill.), Cliff Green (NSSL), Carl Kreitzberg (Drexel Univ.), Ron Reinhart (Univ. of North Dakota), Hap Terry (Univ. of Washington), Tom Seliga (Univ. of Washington)
ROBOT (Mesonet Display)	Russ Dickerson (Univ. of Maryland)
REORDER (Radar Interpolation)	Carl Kreitzberg (Drexel University)

Table 7. Institutions Utilizing RDSS Software in FY 90.

Radar Perusal and Editor	NSSL, Univ. of Oklahoma, Texas Tech Univ., Silicon Graphics, Sutron Corp., Penn State Univ., Univ. of Alabama, Univ. of Washington, Oregon State Univ., SUN Microsystems, UCLA, Florida State Univ., NOAA WPL, Colorado State Univ., Univ. of Chicago, Australian Bureau of Meteorology Research Center (BMRC), Texas A&M Univ., St. Louis Univ., Univ. of Hawaii, NASA, Dalhousie Univ., North Carolina State Univ., Univ. of Ill., Drexel Univ., Univ. of North Dakota
ROBOT	NASA Langley, NASA Johnson, Colorado State Univ., Sutron Corp., Meso Inc., UCLA, San Diego State Univ., Univ. of Maryland
VAD	Univ. of Helsinki, Florida State Univ., NASA Goddard, Illinois Natural History Society, NOAA ERL, DLR (FRG), Univ. of Washington, Univ. of Hawaii, Drexel Univ.
REORDER	Oregon State Univ., UCLA, NOAA WPL, Colorado State Univ., Univ. of Chicago, NASA Huntsville

Development Activities

- A comprehensive prototype software system for real-time and postanalysis data display and integration has been developed for use in the field control center (FCC) application. The software development team was headed by Jon Corbet and included Christopher Burghart, Sandra Yuter (RAP), and Sherry Comes (RAP). Cynthia Mueller and Wilson provided scientific guidance and user requirements to the team. A first field test of the prototype system is planned for the CaPE program in the summer of 1991.

- Richard Oye developed and refined new utilities for handling of data sets on Exabyte cassettes. He also began collaboration with RAF staff on advanced development of interactive software for analysis of aircraft data.

- Burghart prepared significant upgrades to the functionality of the System for User Editing and Display of Soundings (SUDS). Working with Mueller, he developed cross-section display capability derived from two or more soundings.

- Forrest Cook pursued development of next-generation PAM-II configuration editor software. Completion in early FY 91 is expected.

- The RDP programming team collectively accomplished the massive conversion of existing Cray data access, processing, and analysis software to run under the UNIX environment of NCAR's new Y-MP supercomputer.

In addition to software development, a significant portion of RDP programming staff time is devoted to user consulting, software maintenance, and system and network management. In FY 90, RDP staff have served on the SCD User Group and the MSS and Distributed Computing Inventory advisory committees.

Design and Fabrication Services

Missions and Goals

The primary goals of DFS are to provide engineering service through the Mechanical Design Group, fabrication service through the Machine Shop, and logistics and maintenance support through the Logistics Group. The Mechanical Design Group often participates in project efforts by contributing development team members. The Machine Shop performs machining, welding, sheet metal fabrication, cleaning and anodizing, electropolishing, and assembly and repair service. The Logistics Group provides logistics services, equipment maintenance and repair, and general site maintenance for the Marshall site.

The Mechanical Design Group and Machine Shop provide service to all of NCAR, while the Logistics Group activities are generally limited to ATD, with the prime focus on the RSF radars.

Activities of the Past Year

Major development efforts that involved the Mechanical Design Group and/or the Machine Shop included the following:

- profiler drive system (SSSF; Cole)

- aircraft air sampling inlets (University of Rhode Island; Huebert)

- Mile High Radar (RSF; Pratt)

- ASTER (SSSF; Horst, Delany)

- CP-3 and CP-4 radar upgrades (RSF; Lewis)
- CSU CHILL radar (CSU; Mueller)
- mobile CLASS (SSSF; Cole).

Machine Shop support was distributed among the various NCAR divisions and other groups as follows:

Table 8. Machine Shop Support.

	Hours	Percent
Atmospheric Technology Division	6230	53.2
Atmospheric Chemistry Division	3079	26.3
High Altitude Observatory	696	5.9
Colorado State University	443	3.8
Other	367	3.1
NCAR Director's Office	211	1.8
University of Rhode Island	180	1.5
National Institute of Standards and Technology	160	1.4
Scientific Computing Division	152	1.3
National Aeronautics and Space Administration	100	0.8
Mesoscale and Microscale Meteorology Division	72	0.6
University Corporation for Atmospheric Research	20	0.2
Total Hours Charged	11,710	

Staff and Visitors

Division Director's Office

Karen Bowie (50%)
Richard Carbone (director)
Lisa Cummins
Warren Johnson (assistant director)
Will Piper
Robert Snow
Shelley Zucker

Research Aviation Facility

Herminio Avila
Linda Banks
Harold Barber
Darrel Baumgardner
Jeffery Berry
Jeffrey Bogen
Henry Boynton
Edward Brown
Robert Carl
Celia Chen (50%)
Rene Clifford
William Cooper (50%)
Michael Daniels
William Dawson
James Dye (33%)
Richard Friesen
Lowell Genzlinger
Vincent Glover
Joanne Graham
Mary Griffith (75%)
Bryant Heberlein
Michael Heiting
Victoria Holzhauer
Gary Horton
Warren Johnson (manager, to 2/2/90)
Katherine Knepper
Gregory Kok (50%)
Paul LeHardy
Donald Lenschow (33%)
James Lundahl
David McFarland
Erik Miller (50%)
Robert Olson
Jerry Pelk
James Ragni
Edward Ringleman
Ronald Ruth (50%)
Allen Schanot
Ronald Schwiesow
Michael Spowart
Paul Spyers-Duran
Donald Stone
Richard Taylor
Jerry Tejcek
Kim Weaver
Norman Zrubek (acting manager, 2/3–9/30/90)

Surface and Sounding Systems Facility

Edgar Aden
Gerald Albright
Karen Bowie (50%)
Joost Businger (15%)
Edward Chamberlain
Harold Cole
Forrest Cook (25%)
Walter Dabberdt (manager)
Celia Darnell
Anthony Delany
Tom Gardner
Ray Giles
Terrence Hock
Thomas Horst
Catherine Irwin
Kurt Knudson
Errol Korn
Vincent Lally
Dean Lauritsen
Charles Martin
Matthew Michaelis
John Militzer
Claude Morel (50%)
Santiago Newbery
Kenneth Norris
James Owens
Carmen Paneitz
Mary Ann Pykkonen
Steven Semmer
Sigvard Stenlund
Matthew St. John (student)
Marcel Verstraete
Charles Wade (33%)
Gary Wright

Remote Sensing Facility

Patricia Alonzo
Jose Alvistur
Gary Blair
Robert Bowie

Shawn Copeland
Jill Devine
Donald Ferraro
Charles Frush
Richard Gagnon
Jack Good
Grant Gray
Peter Hildebrand (manager)
Jean Hurst (38%)
William Irwin
Jeff Keeler
Brian Lewis
Jon Lutz (75%)
Steve Maher
Richard Neitzel
Richard Parsons
Frank Pratte
Mitch Randall
Robert Rilling (50%)
Michael Strong
Hung Viet Ta
Margaret Taylor
Joseph VanAndel
Joseph Vinson
Craig Walther
James Wilson (50%)
James Ziese

Research Data Program

Christopher Burghart
Celia Chen (50%)
Forrest Cook (75%)
Jonathan Corbet
Paul Herzegh (manager)
Jean Hurst (38%)
Erik Miller (50%)
Claude Morel (50%)
Cynthia Mueller (38%)
Richard Oye
Robert Rilling (50%)
Ron Ruth (50%)

Design and Fabrication Services

Page Baptist
Jeff Bobka
Richard Bobka
Jim Ellis
Jack Fox
Paul Geisert
Alfred Hansen
Michl Howard
Paul Johnson (manager)
Ivan Lee
Hayden Mathews
Alvin Sapp
Kevin Scott
Bart Woodiel
William Zelt

Visitors

Albert Chiang; Taiwan Power Company; 29 March to 24 April 1990; SSSF

Mikhail Fedorov; Academy of Sciences of the USSR, Moscow; 3 September to 26 October 1990; SSSF

David Johnson; unaffiliated; 14 March 1990 through 30 September 1990; RSF

Robert Knobben; New Zealand Meteorological Service, Wellington; 7 February to 10 November 1990; SSSF

Wim Kohsiek; Royal Netherlands Meteorological Institute, De Bilt; 31 August to 15 October 1990; SSSF

R. Paul Lawson; SPEC Incorporated, Boulder, Colorado; 14 May 1990 to 30 September 1990; RAF

Wen Chau Lee; University of California, Los Angeles; 27 December 1988 through 30 September 1990; RSF

Diana Rogers; Stanford University, Palo Alto, California; 25 July to 30 September 1990; RAF

Jacques Testud; Center for Research in the Physics of the Terrestrial and Planetary Environment, Issy-Les-Moulineaux, France; 2 July through 3 August 1990; RSF

Lev Tsvang; Academy of Sciences of the USSR, Moscow; 3 September to 26 October 1990; SSSF

Cynthia Twohy, University of Washington, 1 June 1988 to 1 June 1990; RAF

Sergei Zubkovski; Academy of Sciences of the USSR, Moscow; 3 September to 26 October 1990; SSSF

Publications

Refereed Publications

BUSINGER, J.A., W.F. DABBERDT, A.C. DELANY, T.W. HORST, C.L. MARTIN, S.P. ONCLEY AND S.R. SEMMER, 1990: The NCAR Atmosphere-Surface Turbulent Exchange Research (ASTER) Facility. *Bull. Am. Meteorol. Soc. 71,* 1006-1011.

——, ——, ——, ——, ——, ——, and ——, 1990: The NCAR Atmosphere-Surface Turbulent Exchange Research Facility at NCAR. *EOS 71,* 8 May, 693-702.

——, and A.C. DELANY, 1990: Chemical Sensor Resolution Required for Measuring Surface Fluxes by Micrometeorological Techniques. *J. Atmos. Chem. 10,* 399-410.

CARBONE, R.E., *J.W. CONWAY, N.A. CROOK, and M.W. MONCRIEFF, 1990: The Generation and Propagation of a Nocturnal Squall Line. Part I: Observations and Implications for Mesoscale Predictability. *Mon. Wea. Rev. 118, (1),* 26-49.

——, B. FOOTE, M. MONCRIEFF, *T. GAL-CHEN, *W. COTTON, M. HJELMFELT, *F. ROUX, *G. HEYMSFIELD, and *E. BRANDES, 1990: Convective Dynamics: Panel Report. In*Radar in Meteorology,* Chapter 24b, (David Atlas, Ed.), AMS, Boston, Mass., 391-400.

*CHATFIELD, R.B., and A.C. DELANY, 1990: Convection Links Biomass Burning to Increased Tropical Ozone: However Models will tend to Overpredict Ozone. *J. Geophys. Res., 11,* 18473-18488.

CROOK, N.A., R.E. CARBONE, M.W. MONCRIEFF and *J.W. CONWAY, 1990: The Generation and Propagation of a Nocturnal Squall Line. Part II: Numerical Simulations. *Mon. Wea. Rev. (1),* 50-65

*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.

DYE, J.E., B.W. GANDRUD, and D. BAUMGARDNER, 1990: A Survey of Particle Measurements in the Arctic from the Forward Scattering Spectrometer Probe Model 300. *J. Geophys. Res. 17,* 409-412.

——, ——, ——, *K.R. CHAN, *G.V. FERRY, *M. LOEWENSTEIN, *K.K. KELLY, and *J.C. WILSON, 1990: Observed Particle Evolution in the Polar Stratospheric Cloud of January 24, 1989. *J. Geophys. Res. 17,* 413-416.

GANDRUD, B.W., J.E. DYE, D. BAUMGARDNER, *G.V. FERRY, *M. LOEWENSTEIN, *K.R. CHAN, *L. SANFORD, *B. GARY, and *K.KELLY, 1990: The January 30, 1989 Arctic Polar Stratospheric Clouds (PSC) Event: Evidence for a Mechanism of Dehydration. *J. Geophy. Res. Let. 17,* 457-460.

HILDEBRAND, P.H., and *R.K. MOORE, 1990: Meteorological Radar Observations from Mobile Platforms. In *Radar in Meteorology* , Chapter 22a, (David Atlas, Ed.), AMS, Boston, Mass., 287-314.

*HOOKE, W.H., *D.L. ALBRITTON, R.E. CARBONE, *T. GAL-CHEN, *C.W. KREITZBERG, *C.G. LITTLE and *H. TENNEKES, 1990: Report of the Critical Review Panel - Lower Tropospheric Profiling Symposium: Needs and Technologies. *Bull. Am. Meteorol. Soc. 71(5),* 680-690.

KEELER, R.J., and *R.E. PASSARELLI, 1990: Signal Processing for Atmospheric Radars. In *Radar in Meteorology,* Chapter 20a, (David Atlas, Ed.), AMS, Boston, Mass., 199-229.

*PINKSTERBOER, E.F., *J.-W. ERISMAN, *H.F.M.MAAS, *W.A.H. ASMAN, *A. WAIJERS-YPELAAN, *J. SLANINA, and T.W. HORST, 1989: Gradients of the Ammonia Concentration in a Nature Reserve: Model Results and Measurements. *Atmos. Environ. 23,* 2259-2265.

SERAFIN, R.J., and W.F. DABBERDT, 1990: Profiling Networks and Developments in the United States. *Meteorologische Rundschau, 42,* 70-83.

*SMITH, W.L., *H.E. RVERCOMB, *H.B. HOWELL, *H.M WOOLF, *R.O. KNUTESON, *R.G. DECKER, *M.J. LYNCH,* E.R. WESTWATER, *R.G. STRAUCH, *K.P. MORAN, *B. STANKOV, *M.J. FALLS, J. *JORDAN, *M. JACOBSEN, W.F. DABBERDT, R. McBETH, G. ALBRIGHT, C. PANEITZ, G. WRIGHT, *P.T. MAY, and *M.T. DECKER, 1990: GAPEX - A Ground-based Atmospheric Profiling Experiment. *Bull. Am. Meteor. Soc., 71(3),* 310-318.

WILSON, J.W., 1990: Aviation Meteorology: Panel Report. In *Radar in Meteorology* , Chapter 31b, (David Atlas, Ed.), AMS, Boston, Mass., 692-688.

*WOFSY, S.C., *R.J. SALAWITCH, *J.H. YATTEAU, *M.B. McELROY, B.W. GANDRUD, J.E. DYE, and D. BAUMGARDNER, 1990: Condensation of HNO3 on Falling Ice Particles: Mechanism for Denitrification of the Polar Stratosphere. *J. Geophy. Res. 17,* 449-452.

Other Publications

*BADER, D.C., and T.W. HORST, 1990: Model Evaluation of the Assumptions Used in Valley Energy Budgets. In *Proc. of the Fifth Conference on Mountain Meteorology,* Boulder, Colo., June, 1990. AMS, Boston, Mass., 277-280.

* An asterisk denotes a non-NCAR author

BAUMGARDNER, D., and *M. HAGEN, 1990: Estimates of ice particle bulk densities and total water mass in an upslope-generated cloud. In *Preprint Vol., Conference on Cloud Physics*, San Francisco, Calif., 23-27 July, 1990. AMS, Boston, Mass., 8-15.

——, and *A. JOCHUM, 1990: Distribution of Atmospheric Aerosols during Development of Boundary Layer Clouds. In *Preprint Vol., Conference on Cloud Physics*, San Francisco, Calif., 23-27 July, 1990. AMS, Boston, Mass., 531.

DABBERDT, W.F., and R.M. HARDESTY, 1990: Summary of the Symposium on Lower Tropospheric Profiling: Needs and Technologies, 31 May-3 June, 1990, Boulder, Colo. *Bull. Am. Meteor. Soc., 71 (5)*, 665-671.

——, and *W.G. HOYDYSH, 1990: Investigation of Quantitative Applications of Video Imaging Systems to Fluid Modeling Studies of Turbulence and Dispersion. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, Roskilde, Denmark, 30 April-3 May, 1990. AMS, Boston, Mass., 180-183.

JOHNSON, D.B., and R.M. RASMUSSEN, 1990: On the Transition between Wet-Growth and Dry-Growth for Graupel and Hail. In *Preprints Vol., Conference on Cloud Physics*, San Francisco, Calif.,23-27 July, 1990. AMS, Boston, Mass., 278-281.

LALLY, V.E., D. LAURITSEN, T. HOCK, and K. NORRIS, 1990: Wind Measurements over the North Atlantic Using a Loran-C Dropwindsonde. *J. Institute of Navigation, 36, No. 4*, Winter, 363-372.

LEE, W-C, R.E. CARBONE, and *F.D. MARKS, 1990: Real-Time Measurement of Hurricane Circulation Using Airborne Doppler Radar - Velocity Track Display. In *Proc. Conference on Weather Radar and Flight Safety*, Taipei, Taiwan, Republic of China, 10-11 May, 1990. Taiwan Civil Aeronautics Administration, 21-26.

ONCLEY, S.P., J.A. BUSINGER, *C.A. FRIEHE, *J.C. LaRUE, *E.C. ITSWEIRE, and *S.S.CHANG, 1990: Surface Layer Profiles and Turbulence Measurements over Uniform Land under Near-Neutral Conditions. In *Preprint Vol., Ninth Symposium on Turbulence and Diffusion*, Roskilde, Denmark, 30 April-3 May, 1990. AMS, Boston, Mass., 237-240.

RANDALL, M., 1990: Harmonic Suppressing Digital Frequency Divider, *RF Design*, August, 55-63.

SCHWIESOW, R.L., M.P. SPOWART, V.M. GLOVER, and *P.W. YOUNG, 1990: Design of an Airborne Heterodyne Lidar for Atmospheric Wind Measurements. In *Abstracts of Papers, 15th International Laser Radar Conference*, Tomsk, USSR, 23-27 July, 1990, Inst. Atmos. Optics, Tomsk, USSR, Part I, 40-43.

* An asterisk denotes a non-NCAR author.

NCAR Annual Scientific Report Fiscal Year 1990 - Link Page

National Center for Atmospheric Research
Annual Scientific Report
Fiscal Year 1990

Submitted to National Science Foundation
by
University Corporation for Atmospheric Research
June 1991

Scientific Computing Division

Introduction

The NCAR Scientific Computing Division (SCD) provides supercomputing resources and services that support research in the atmospheric, oceanic, and related sciences. We emphasize facilities for the development and execution of large models and archiving and manipulation of large data sets.

Since access to supercomputers and data is fundamental to research in the geosciences, the principal mission of SCD is to provide:

- supercomputing resources to develop and execute large numerical simulations and to archive and manipulate large data sets,
- network and data communications capabilities required for an international user community to access NCAR computational and data resources, and
- a computing environment that emphasizes reliability, high performance, graphical display, and user productivity.

Organization

To support this mission, we have assembled a computing network that offers a variety of hardware, software, and communication facilities. Functionally, the NCAR computing network contains four components: (1) mainframe computing systems, (2) communications systems, (3) network servers, and (4) the Mainframe and Server Network (MASnet) and the Local Data Network (LDN). These four components are accompanied by a variety of user support services.

A diagram of these components is shown in Figure 1. A chart of our organization in support of these functions is shown in Figure 2.

Significant Accomplishments

- While the NSF portion of the SCD budget increased by only 1.68% over fiscal year 89, we managed to avoid a major reduction in staff by taking cost-control measures and finding some non-NSF funding. Cost-control actions included encouraging university scientists to reduce their use of SCD-financed communication options, retiring older equipment, and making greater use of in-house maintenance expertise. Non-NSF funding included cost-recovery income from use of the CRAY X-MP/18 by the Environmental Protection Agency (EPA) and grants from NOAA, the Department of Energy (DOE), and the Office of Naval Research to support research by NCAR scientists.
- We performed the following upgrades:
  - installed a CRAY Y-MP8/864 supercomputer with eight processors, 64 million words of memory, a 256-million word solid-state storage device (SSD), and 60 billion bytes of disk storage
  - upgraded the mass storage system (MSS) controller to an IBM 3090 Model 110J with 32 million bytes of memory and 16 input/output (I/O) channels

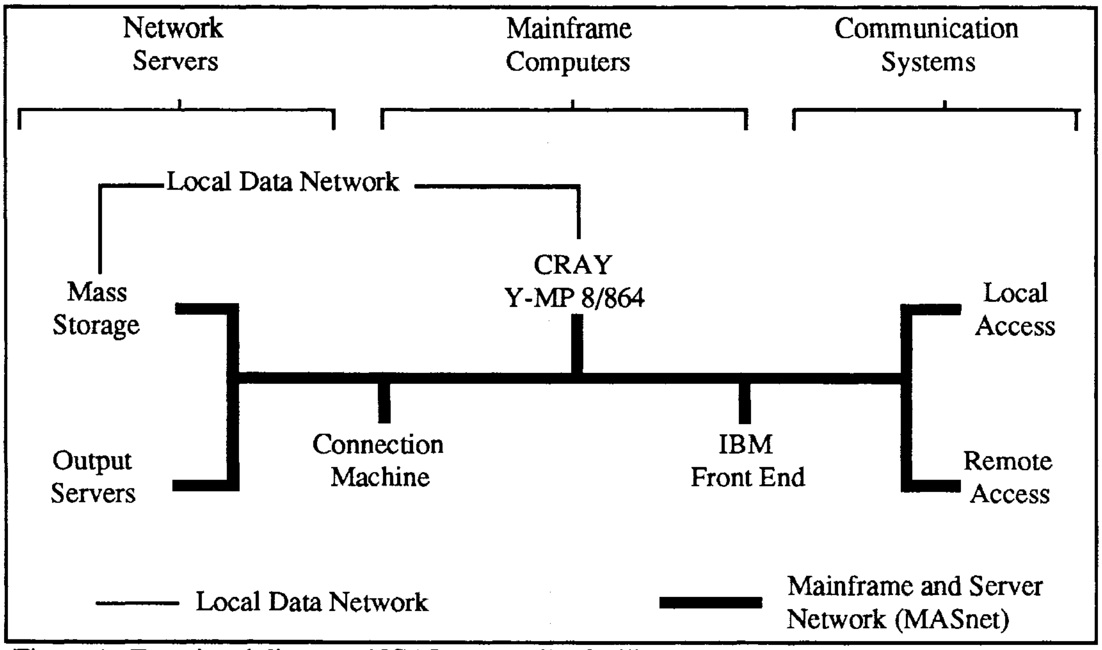

Figure 1. Functional diagram, NCAR computing facility.

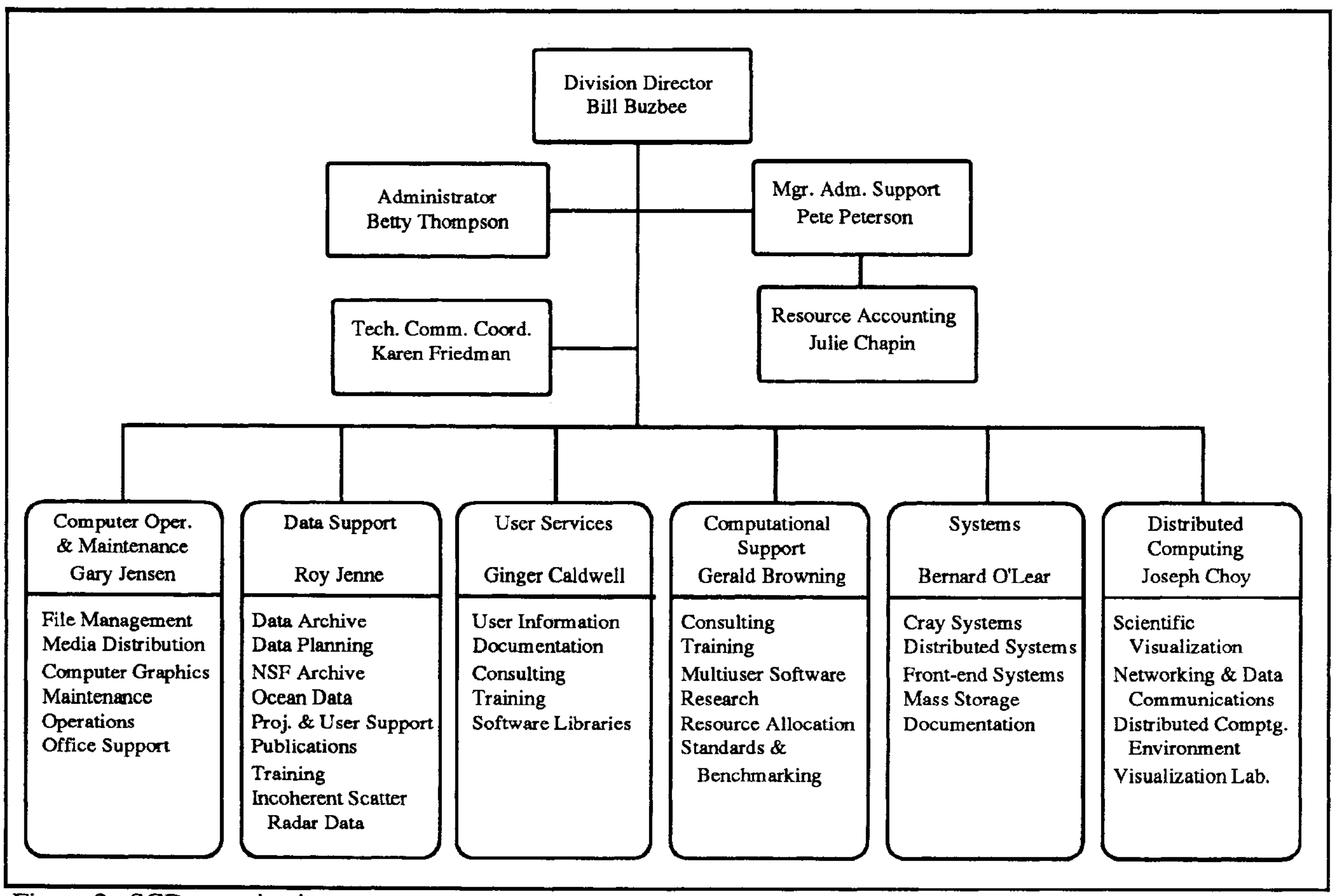

Figure 2. SCD organization.

- added more cartridge read/write stations to the StorageTek 4400 Automatic Cartridge System (ACS) acquired in FY 89
- installed upgrades to our network gateways to provide additional processing power and disk storage capacity
- attached the Uninterruptible Power Supply (UPS) to our film-processing equipment
- acquired an additional Dicomed color film processor
- acquired video recorders, editing equipment, a frame recorder, and other devices with which to develop an interactive video production facility.

• SCD acquired or introduced a number of new capabilities:

- began running jobs under UNICOS on the CRAY Y-MP. UNICOS is the version of UNIX supported by Cray Research, Inc. It offers interactive debugging and graphics. It also makes possible exploitation of distributed computing technologies such as the X Window System, Network Queueing System (NQS), and Network File System (NFS).
- added the Advanced Interactive Executive (AIX/370) operating system to the IBM front-end (FE) machine, thus providing a UNIX alternative to users of this system.
- launched the Text and Graphics System (TAGS) into full production. This is a UNIX-based output spooling and control system that supports all the functionality of the Graphical Kernel System (GKS) version of NCAR Graphics as well as the emerging NCAR Raster Graphics Format. Support for pre-GKS NCAR Graphics was discontinued.
- developed a phased plan for providing high-speed communications between the Mesa Laboratory and the new NCAR North campus.
- doubled the aggregate bandwidth of the fastpath between the CRAY Y-MP and the Mass Storage System (MSS).
- created a journal database for the NCAR Library.
- developed UNICOS accounting software that meets specific NCAR requirements.
- developed a Large Model (LM) queue (formerly called job class) on the Y-MP to expedite execution of large, long-running simulations. NCAR plans to identify simulations with high scientific potential and spend about 25% of its allocated Y-MP resources using the LM class to process them.

• SCD wired a record number of communication nodes throughout NCAR and UCAR and manually loaded a record 47,000 cartridges on the MSS during September (the last month of the CRAY X-MP/48 operation with COS).

• The following advances were made in software:

- completed and distributed Version 3.00 of the NCAR Graphics package and *NCAR View: A CGM Translation and Manipulation Package (NCAR View Version 3.00)*. This version includes new graphics capabilities, an interactive display tool (IDT), and support for additional output devices.

- extended the Internet Remote Job Entry (IRJE) system and the MASnet Internet Gateway System (MIGS) functionality to provide access to the extended Mass Storage System and TAGS.
- put our Systems Configuration and Interconnection Document (SCID) facility into production.
- made a number of enhancements to electronic mail (e-mail) on an NCAR-wide basis.
- incorporated the CRAYFISHPAK and LAPACK mathematical subroutine libraries into our software library system.
- made significant enhancements to the MUDPACK mathematical software suite.

• In the area of documentation and training, SCD published the *NCAR UNICOS Primer* and *COS-UNICOS Conversion Guide*, support staff taught UNICOS orientation and UNICOS conversion training classes, and also significantly increased online documentation. In FY 90, we produced 26 online user documents and 14 locally written *man* pages.

• SCD provided satellite data for a major NASA study of world temperature trends. The division also participated in several international data exchanges, including the receipt of 12 million ship observations from the USSR for 1898–1990.

• A videotape on the use of the NCAR Mass Storage System in studies of global change, developed jointly by SCD's Operations and User Services sections, was one of five finalists for the *Computerworld* Smithsonian Award for innovative use of technology on behalf of society.

• A list of the meetings for which several NCAR staff provided support follows.

Site Liaison Workshop. SCD staff organized and participated in the Site Liaison Workshop, which was held 24–29 June at NCAR, to train NCAR's site liaisons in using UNICOS and converting codes from COS to UNICOS. Site liaisons from 6 NCAR divisions and 20 universities, all experienced users, assist other NCAR supercomputer users in their department or division. The workshop provided advanced lectures on a variety of computing topics and hands-on lab sessions using the CRAY Y-MP8/864 computer.

CAS90. SCD staff hosted the 1990 Computing in the Atmospheric Sciences Conference (CAS90), held 10–13 September in Gleneden Beach, Oregon. CAS90 focused on the interaction among computing, atmospheric, and oceanic sciences. Conference participants discussed the current status of data management, modeling, and computing, then analyzed their future needs. Participants were from industry, the national laboratories, and U.S. and foreign federal agencies.

Tenth IEEE Mass Storage Symposium and *Digest of Papers*. Members of SCD served on the organizing committee for this event, sponsored by the Institute of Electrical and Electronics Engineers (IEEE) Computer Society. The meeting was held 7–10 May in Monterey, California, to address the crisis brought on by the chasm between isolated developments in advanced computing hardware and the relatively limited progress in the development of total storage systems to satisfy specific applications problems. SCD staff were responsible for local arrangements, registration, and editing and producing the symposium proceedings. Participants represented industry, the national laboratories, U.S. and foreign universities, and U.S. federal agencies.

IEEE Storage Systems Standards Working Group. SCD staff hosted two meetings of the IEEE Storage Systems Standards Working Group, held 25–26 July and 17–18 September at NCAR. These meetings were held so workshop participants from industry, universities, and the national laboratories could discuss and ultimately recommend standards to industry for an overall mass storage system architecture. SCD staff provided logistical support for this meeting.

Executive Committee of the IEEE Mass Storage Systems and Technology Technical Committee (MSSTC). Three IEEE MSSTC meetings were held at NCAR: 26–27 February, 14–15 June, and 15–16 October, and were hosted by SCD staff who are also committee members. The purpose of the meetings was to discuss final preparations for the Tenth IEEE Mass Storage Symposium and plans for the Eleventh Symposium. SCD staff provided logistical support for this meeting.

SLATEC Graphics Group. SCD hosted the SLATEC Graphics Workshop 20–21 September at NCAR. (SLATEC stands for Sandia National Laboratories, Los Alamos National Laboratory, and the Air Force Weapons Laboratory Technical Exchange Committee.) The key items of discussion included NCAR Graphics Version 3.01, PolyPaint, SLATEC File Transfer Protocol (FTP) software distribution, the SLATEC Application Visualization System (AVS) module pool, data compression of raster images, the scientific visualization reference model, and the SLATEC membership agreement. Participants were from industry, universities, U.S. governmental agencies, the national laboratories, and supercomputer centers. SCD provided logistical support for this meeting.

Sixth Forum on Computer Systems for Documentation. SCD staff hosted and served on the organizing committee for the Sixth Forum on Computer Systems for Documentation, held 7–10 November 1989, in Estes Park, Colorado. The purpose of the meeting was to provide an arena for the exchange of information and ideas among people who are responsible for documentation systems at DOE facilities and related laboratories. SCD staff were responsible for local arrangements, registration, and audio/visual requirements.

Workshop on Online Documentation in the Supercomputing Environment. SCD and Los Alamos National Laboratory staff members jointly organized and hosted this workshop held 3–6 April in Colorado Springs, Colorado. Twenty-eight participants from twelve supercomputing centers, as well as Cray Research and IBM, exchanged ideas about the need for a common online documentation system that could serve a heterogeneous distributed computing environment. SCD staff were responsible for local arrangements, registration, and audio/visual requirements, in addition to sharing the program responsibilities.

DISCOS. SCD hosted the DISCOS (Distributed Computing Solutions) Users Group meeting 19 September at NCAR. DISCOS is a division of General Atomics, San Diego, CA. SCD staff provided logistical support for this meeting.

CHAMMP Interagency Organization for Numerical Simulation (CHAMMPions). SCD hosted the first organizational meeting for the CHAMMPions project 23–24 April at NCAR. (CHAMMP stands for Computer Hardware, Advanced Mathematics, and Model Physics.) The CHAMMPions project is run jointly by Argonne National Laboratory, Oak Ridge National Laboratory, and NCAR. It is funded by the DOE CHAMMP initiative, whose long-term objective is to develop an advanced climate model for massively parallel computer architectures. SCD staff provided logistical support for this meeting.

ACTS. SCD hosted the Advanced Communications Technology Satellite (ACTS) Gigabit Applications Workshop 10–11 April at NCAR. The objectives were to identify high data rate applications and their benefits, develop ACTS experiment scenarios, and identify organizations interested in planning and further developing the details of an ACTS experiment. Participants included representatives from U.S. federal government agencies, the national laboratories, and selected universities. SCD staff provided logistical support for this meeting.

- SCD participated in meetings that involved gathering information about available data, planning for the acquisition of new data, and discussing information on associated science. The activities included participating in projects in Australia and Brazil, attending a World Meteorological Organization meeting on baseline data sets (for example, data for polar regions), and preparing bilateral exchange agreements with the USSR.

Workload

Because of the partnership between NCAR and universities, SCD provides computing resources to both university and NCAR scientists. During FY 90, approximately 740 researchers distributed throughout academe and 460 researchers at NCAR used the computing facility.

Potential users must receive an allocation of General Accounting Units (GAUs) to use SCD's computers (explained in "Resource Accounting and Control," below). Table 1 shows GAU usage by broadly defined scientific disciplines.

Communication Systems

For most scientists, desktop computers and/or departmental computers provide the primary means of software development and postanalysis of results. SCD collectively refers to these systems as user nodes, and invariably they need to communicate with other computing systems via networks in a distributed computing environment. Through the technologies of communications, local-area networks, wide-area networks, network gateways, user workstations, and window interfaces, SCD is assimilating the user nodes into an integrated environment with the mainframes and network servers of the NCAR computing facility.

Local Access

Due to a combination of ethernet technology, the Transmission Control Protocol/Internet Protocol (TCP/IP), other protocols, and network gateways, most NCAR divisions enjoy full interconnectivity, including access to the NCAR supercomputer facilities. The ethernets, which link together the NCAR and UCAR organizations, are known as UCARnet. In addition, SCD offers the usual array of dedicated and dial-up circuits by which mainframe systems can be accessed from dumb terminals via a 1024 x 1024 port switch. SCD is responsible for communication links throughout NCAR's organizational units in Boulder County that support voice, data, and slow-scan video services.

With UCAR's purchase of the NCAR North facilities, it is anticipated that by mid-1991, most of NCAR and NCAR organizational units will be located at either the Mesa Laboratory or at NCAR North. Figure 3 shows proposed associated communications links between these two sites.

Remote Access

With the advent of modern networking technology, national and international networks offer an attractive avenue of access for remote users; in particular, they offer relatively high bandwidth. Consequently, SCD has moved rapidly to be a node on selected national and international networks. The division is on the NSFNET backbone, the NASA Science Network

Table 1. GAU Allocation

Area of Interest	% GAU Use
Climate	**35**
Climate	
General circulation	
Radiative processes	
Satellite meteorology	
Statistical meteorology	
Oceanography	**13**
Basic Fluid Dynamics and Miscellaneous	**7**
Basic geophysical fluid dynamics	
Numerical methods	
Turbulence	
Wave processes	
Economic and societal impact studies	
Computer science	
Other	
Regional Meteorology	**26**
Planetary boundary layer	
Dynamic meteorology	
Mesoscale and regional-scale models	
Surface conditions, hydrology	
Tropical meteorology	
Numerical weather prediction	
Objective analysis and diagnostic studies	
Chemistry and Upper Atmosphere	**7**
Aerosol physics	
Atmospheric chemistry	
Upper atmosphere dynamics and aeronomy	
Cloud Physics	**8**
Radar meteorology	
Severe storm and cloud physics	
Data processing (aircraft, balloon)	
Astrophysics	**4**
Astrophysics	
Solar interplanetary medium	
Solar physics	
Physics of planetary atmospheres	
Solar-terrestrial relations	
Magnetohydrodynamics and plasma physics	
Total	**100**

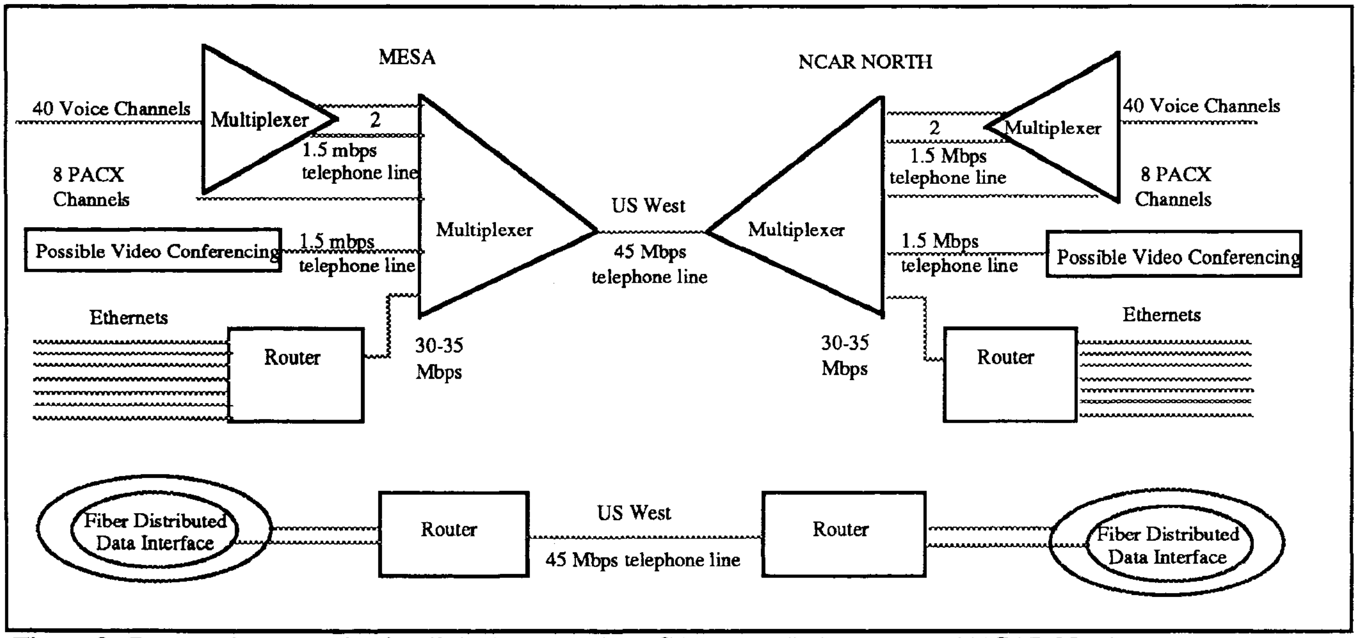

Figure 3. Proposed communication links between the NCAR Mesa Laboratory and NCAR North.

(NSN), NASA's Space Physics Analysis Network (SPAN), and BITNET, which offers mail file transfer and remote job entry (RJE) facilities to/from the IBM 4381 front-end computer Also, SCD manages the University Satellite Network (USAN) that uses satellite technology for high-speed network access. USAN connects NCAR with six remote satellite sites in the atmospheric, oceanic, and related sciences. This discipline-oriented, midlevel network also connects these sites to the resources available through NSFNET, NSN, and SPAN. SCD operates an Internet network satellite link to the Universidad Nacional Autonoma de Mexico and the Instituto Tecnologico y de Estudios Superiores de Monterrey via a network called Red Academica de Mexico. In addition, USAN provides connectivity to NSFNET for several regional networks (see Figure 4).

SCD also acquired public packet network services from SprintNet (formerly Telenet). Using SprintNet, remote users can interact directly with the FE via a telephone call to their local exchange in over 370 cities throughout the United States and in some foreign countries. Associated functionality includes terminal connectivity as well as file transfer. SprintNet bandwidths to NCAR are at most 2400 bits per second (bps).

Networks are a tremendous asset to researchers throughout the community and they are especially valuable to university scientists for accessing the NCAR computing facility.

Mainframe Systems

Mainframes in the SCD network include a CRAY Y-MP8/864, an IBM 4381 I/O front-end system, and a Connection Machine 2 (CM-2).

NCAR's CRAY Y-MP8/864 supercomputer, delivered in May 1990, completed its acceptance tests on June 19 and has been available for use since that time. This machine runs UNICOS, the UNIX-based operating system for Cray computers. The Y-MP has 8 central processing units, 64 million words of central memory, an internal speed of 6 nanoseconds per calculation, a 256-million-word SSD, and 60 billion bytes of disk storage. Called "shavano," the supercomputer is named for Mount Shavano, one of Colorado's 14,000-foot peaks.

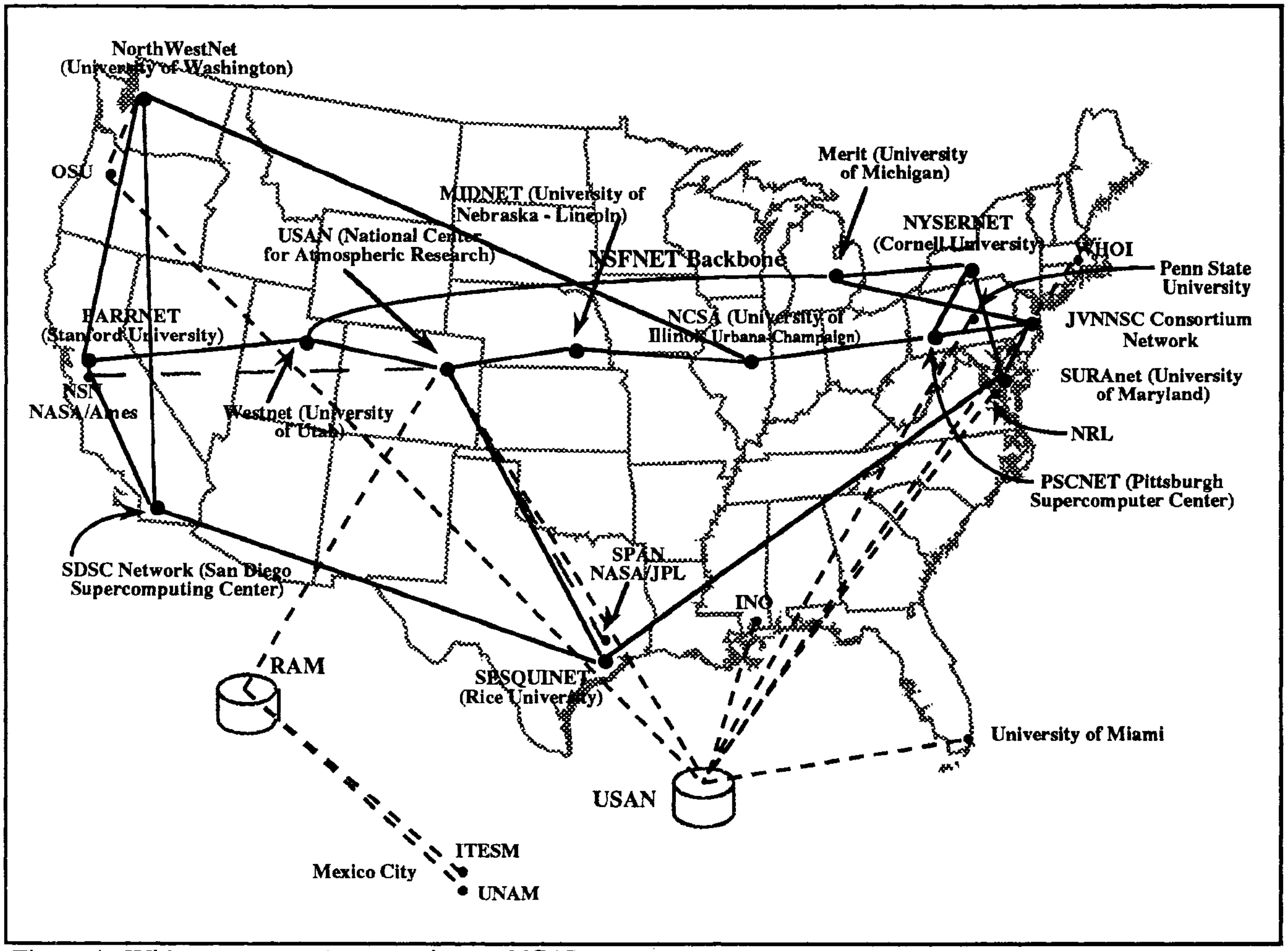

Figure 4. Wide-area network connections at NCAR.

The IBM 4381 is configured to support interactivity and was originally acquired as a front end for supercomputers with batch operating systems. It has dual processors, 24 megabytes (MB) of memory, 20 gigabytes (GB) of disks, and 126 ports. It uses the IBM Virtual Machine/System Product High Performance Option (VM/SP HPO) and AIX/370 operating systems.

The Connection Machine 2 is an 8192-processor computer, manufactured by Thinking Machines Corporation (TMC), for use by members of the Center for Applied Parallel Processing at the University of Colorado and NCAR. The CM-2 performs thousands of computations simultaneously (in parallel). It is used for algorithmic research and software development in parallel processing. A VAX 8550 is the front-end computer to the CM-2.

Network Servers

Two nodes in the SCD network provide storage and output services respectively to both mainframes and distributed processors. These are the Mass Storage System and the Text and Graphics System. This distribution of functions into specific nodes (servers) makes possible substantial economies in support and expansion of the SCD facilities. Put another way, SCD does not equip its supercomputers with long-term storage devices. Rather, all archival storage is concentrated into the MSS. Similarly, the division does not equip its supercomputers with text or graphics output devices. Instead, output is processed on TAGS.

Mass Storage

The MSS allows users to store and access massive amounts of data. Currently, it holds about 550,000 files totaling 119 terabits (Tb) of information. On a daily basis, the system handles about 5500 requests involving about 1200 gigabits (Gb) (see Figure 5). The NCAR MSS has a hierarchy of three storage levels, each with different access times. The system monitors the frequency with which files are accessed and stores them in this hierarchy accordingly. Frequently used files that are less than 30 MB are kept on disk (level 1); frequently used files that are more than 30 MB are kept on the StorageTek ACS (level 2); and infrequently accessed files are on cartridges that are stored on open shelves (level 3). Thus, frequently accessed files are readily available via either disk or the ACS. This hierarchy, combined with a custom-built fast data path, provides a close coupling between supercomputers and frequently accessed data.

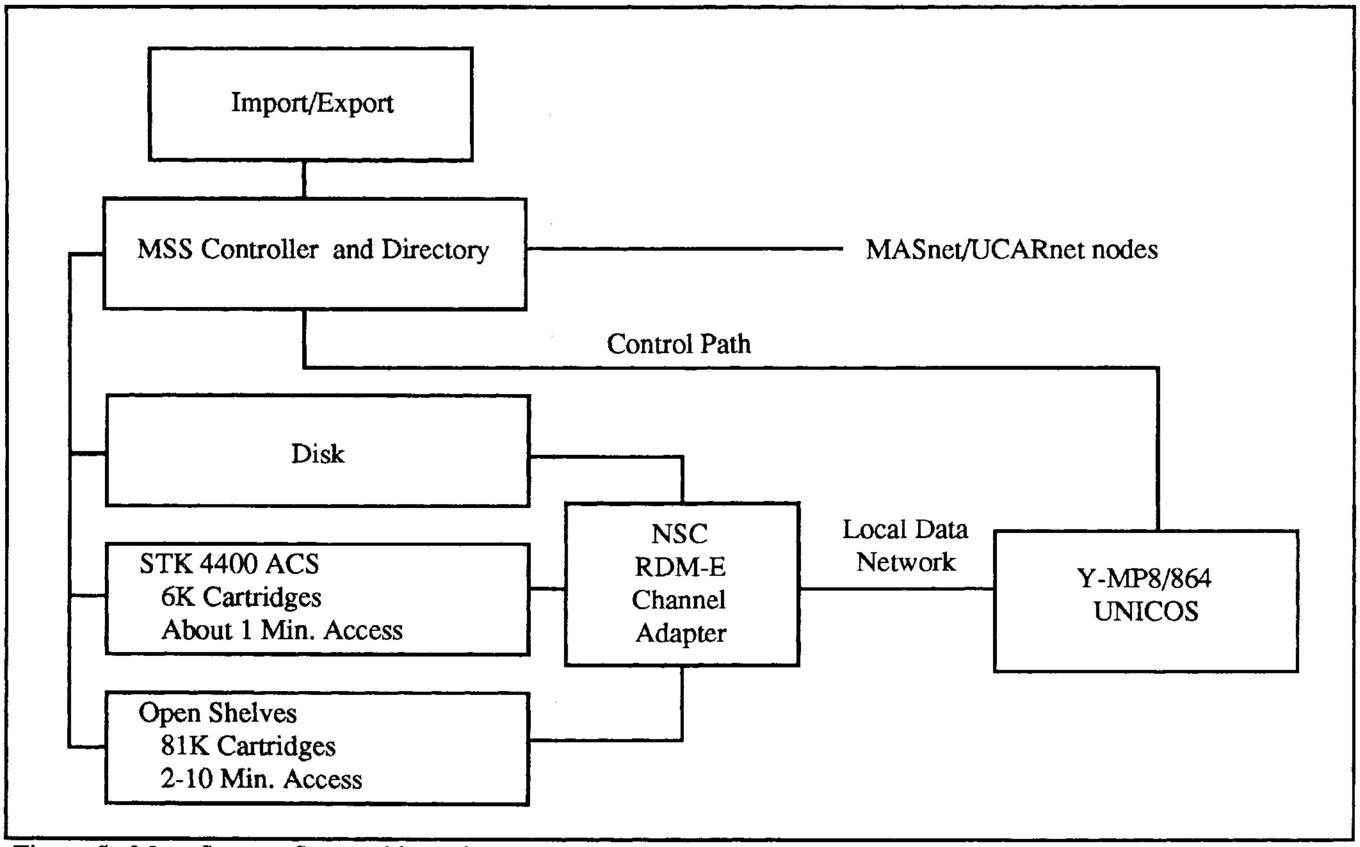

Figure 5. Mass Storage System hierarchy.

The IBM 3480 tape cartridge is the basic storage medium. The cartridge inventory exceeds 81,500 units. Because the system has its own control processor, file purging and data compaction on cartridges are performed as background processing. Overall, the MSS is exceptionally reliable and is generally considered to be the most modern MSS (file) network server in use today.

Text and Graphics System

TAGS conceptually consists of two Xerox 4050 laser printers and four Dicomed film recorders. The laser printer software allows both text and graphic output; SCD produces approximately 15,000 "images" per day. NCAR is one of the few supercomputing centers in the world to offer graphics via laser printers.

The color Dicomeds produce 35-mm color film that can be transformed into slides upon request. The film recorder output may be either 16- or 35-mm film or fiche. On a daily basis, SCD averages about 16,000 frames of fiche and about 3500 frames of 35-mm film.

The laser printers and film recorders are driven by separate systems. The NCAR-provided software running on these systems allows several different input formats (Computer Graphics Metafile or CGM; raster; and text) to be sent to these output devices. Since these systems are attached to MASnet, output can be sent to them from both mainframes and user systems.

Mainframe and Server Network

MASnet provides a hardware/software mechanism for interconnecting the SCD mainframes and servers, as well as providing access to them from UCARnet and national networks (see Figure 1). File transfer, system-status broadcast RJE, distributed printing, and distributed graphical output are the major functions performed by MASnet. MASnet, operational since 1980, has been constructed from Network Systems Corporation (NSC) HYPERchannel hardware components using software developed by SCD.

Currently, MASnet consists of 14 directly attached NCAR nodes, 4 nodes that are attached via Digital Equipment Corporation (DEC) clustering or SCD gateway support, and several NCAR nodes that have indirect MASnet access. This access is provided through such mechanisms as Berkeley Software Distribution UNIX commands and other mechanisms such as NFS. Monthly activity on MASnet currently consists of transferring over 180,000 files containing a total of 72 Gb.

User Support

SCD strives to provide a high level of service to its users and actively solicits their input. The SCD director and several of his staff visit at least six university sites each year in an effort to stay abreast of user issues and to inform university users of SCD's new services and future plans. SCD also encourages user participation through a number of advisory committees. These include:

- The SCD Advisory Panel, composed of 12 appointed representatives from universities and nonprofit research organizations, a representative each from UCAR and NSF, and invited observers. The panel meets twice each year and advises the staff on long-term planning and requests for university computing allocations.

- The SCD Users Group (SCDUG), composed of two representatives from each NCAR division and all interested observers. The group, which meets at NCAR on a monthly basis, has an agenda that covers a broad range of computing issues. Currently, the group is leading a user test of AIX/370 on the IBM 4381.

- The Mass Storage System Advisory Committee, composed of at least one representative and an alternate from each NCAR division. The group meets at NCAR on a monthly basis to provide input for future development and user needs to the Mass Storage System. All interested users are welcome to attend.

- The NCAR Visualization Users Group (NVUG), composed of representatives from each NCAR division and Unidata, UCAR's University Data Project. The group meets on a monthly basis and provides direction to the staff on enhancements to NCAR Graphics and visualization items and reviews software designs and services.

- The SCD User Conference, held at NCAR approximately every 18 months, with all users invited. Conference themes vary, depending on the latest software, hardware changes, and division plans. Attendees are invited to provide planning input and their ideas on current operations.
- Site Liaison Workshop, held at NCAR approximately every two years. Site liaisons who assist users of NCAR supercomputers are invited from over 20 universities to attend and obtain in-depth training. During this week-long workshop, participants are invited to provide their opinions on a variety of computing issues to SCD management.

In addition, SCD uses special advisory groups when specific input is needed, such as the Technical Advisory Group and the Computer Output Committee.

Consulting

To assist scientists in the use of its facilities, SCD provides consulting services, documentation, training, software libraries, and assistance with the installation of the NCAR Graphics package.

User consulting is provided by highly skilled professional programmers 38.5 hours per week via the telephone, electronic mail, or in person. User reviews consistently rate the quality of SCD's user support services as "very good" to "excellent."

A user area providing a variety of graphics workstations and personal computers (PCs) is available to SCD visitors 24 hours a day, seven days a week. A full set of vendor and SCD documentation is available for reference.

Documentation

As the complexity of the supercomputing environment has increased, so has the need for documentation. Because SCD must document locally developed software such as MSS, MASnet, and NCAR Graphics, vendor documentation is insufficient. To fill this need, SCD has developed and maintains a comprehensive set of written and online documentation. A documentation catalog describing SCD and vendor documentation is updated every six months and distributed to all users once a year.

Training

SCD offers training classes for differing user requirements. Each month, SCD's User Services Section provides a two-day UNICOS class at NCAR for new users without UNIX experience and a four-hour course for new users with UNIX experience. By the end of the class, the student gains a basic introduction to the SCD computing environment, including the use of scripts to control job execution under UNICOS and commands to access the Mass Storage System and output servers.

Software Libraries

The SCD-supported applications software contains over 9000 subroutines and functions, spanning 20 mathematical libraries. Requests for new software are given priority according to overall usefulness, quality of software, cost, and effort required to support the product. SCD provides an online database with documentation for most of the mathematical software source code for the nonproprietary libraries.

NCAR Graphics

The NCAR Graphics package provides a wide range of capabilities to scientists and researchers—graphs and grids, contours, halftone contours, dashed lines, maps, area fill, field flows, text labels, legends, three-dimensional displays, color conversion, and moviemaking tools. Its functions are heavily oriented toward organizing large amounts of numerical data and producing concise visual representations of these data. Each of the graphics utilities is a Fortran-callable routine or package of routines for solving relatively complex graphics problems. NCAR Graphics was developed with portability, device independence, and conformance to GKS as key features.

The NCAR Graphics software is now in widespread use in universities and scientific laboratories. It is installed at over 1000 sites and the latest version based on GKS resides at over 500 sites.

Mainframes and Systems Administration

This area of responsibility is shared by SCD staff who provide support to the supercomputer, to the IBM 4381 front-end computer, and to small UNIX systems.

Supercomputer Support

The Systems Section Supercomputer Group maintains and enhances the software systems for the CRAY Y-MP8/864 computer. The Y-MP operating software is composed of three operating systems along with support products, utilities, libraries, and compilers. The UNICOS operating system, an interactive system derived from AT&T UNIX System V, controls the central processor activity. The Input/Output Subsystem, composed of four processors dedicated to communication with networks, peripheral equipment, the MSS, and the Operator Work Station (OWS), has its own non-UNIX operating system. The OWS, which includes a Motorola microprocessor, runs its own version of UNIX.

For the Supercomputer Group, 1990 brought dramatic changes in both computer hardware and software. Two Cray computers were decommissioned and replaced by one with twice their combined power.

After nearly a year of service, serial 331 CRAY X-MP/18 was shut down on 1 March. This single-central-processor Cray computer with eight million words of central memory was the replacement for the decade-old CRAY-1A the year before. In addition to the added computing power, this machine represented a significant step on SCD's path toward a unified UNIX environment at NCAR. The X-MP/18 gave SCD its first experience with UNICOS.

COS saw its last use at NCAR with the shutting down of the CRAY X-MP/48 on October 1. The X-MP/48, installed in 1986, was the four-central-processor, eight-million-word workhorse of SCD. Its 8.5-nanosecond clock period provided reliable supercomputing in the several hundred megaflop range. (Mflop stands for million floating point operations per second.)

The Y-MP8/864 is the latest and most powerful addition to the computing resources at NCAR (see "Mainframe Systems," above). Performing in the gigaflop (Gflop) range (one billion floating point operations per second), the Y-MP represents a significant upgrade to NCAR's computational capacity. Users are increasingly appreciating the advantages of commonality and interactivity as they become familiar with the Y-MP computing environment. The common UNIX interface allows them to easily move from one system to another, taking along a wealth of familiar tools. Interactive symbolic debugging gains adherence as users find that the time to move computer models from checkout to production can be significantly reduced.

IBM 4381 Front End

The 4381 Front-End Group provides support for interactive access to NCAR facilities, especially for users without front-end capability. The IBM 4381 is currently running both IBM's VM/SP HPO operating system and the AIX/370 operating system.

The major effort in FY 90 was to install, test, port applications (such as MASnet) to, and evaluate AIX/370 as a UNIX alternative to CMS on the 4381 front end. IBM's AIX/370 is a real mainframe UNIX, which could satisfy SCD's requirement for a UNIX front-end computer using SCD's current hardware. The primary purpose of this AIX/370 system is to facilitate the conversion of the front-end user base from CMS to UNIX.

NCAR successfully participated in the Early Support Program (ESP) for AIX/370 (and VS Fortran for AIX/370), and thus gained early access to the code. This ESP also allowed early access to the AIX/370 developers and support staff. AIX/370 is now generally available to IBM customers.

The 4381 front end continued to provide a full production CMS front end during the year, with no degradation of CMS service (with the addition of 8 MB of memory). In addition to the CMS environment, the 4381 front end now has a fully capable UNIX system available for general use.

Distributed Computing

The Workstation Interface

SCD supports the concept of a uniform window interface (UWI) to SCD computers. SCD is working with user groups to help set the standards for and develop such an interface. This UWI will support the following functions:

- log-on access to all SCD supercomputer resources and front-end computers
- transparent access to SCD file servers and file archives and the functionality to move files anywhere in the distributed computing environment including the remote workstation
- the provision of workstations to produce graphics generated by other nodes in the SCD distributed environment
- the ability to open process "windows" on the user workstation by processes running on nodes in the SCD distributed supercomputing environment.

SCD continued the development of the UWIs for inexpensive platforms including PCs, Macintosh computers, and UNIX workstations. The division continues to work with the users, both individually and in user groups, to define and refine the functionality and forms of the UWIs that SCD will support and distribute. The current planning view of the UWI is that it will be distributed across workstations, file servers, front ends, and the supercomputers, but it should appear as part of the workstation environment, that is, the distributed UWI should appear seamless to the user. Some of the 1990 UWI development work is listed below.

Window Applications Development Work. The advantage of window managers is that several tasks can run "simultaneously" in a multitasking windowed environment. The users are able to monitor their progress by assigning a window to each task and then interacting with those tasks. The environment of these workstations, supporting gateways, and front ends has been extended to include window applications that provide:

- access to UNIX shell scripts that enhance the interactive connection to the UNIX supercomputers
- access to the routines that perform interactive translation of graphics from NCAR-generated CGM metacode, and that provide on the workstation "bitmap" graphics that have been generated and directly transmitted from another computer
- NFS file service to all workstations in support of the paradigm of network-distributed "file systems"
- an asynchronous archive file service between the MSS and the workstation (release planned spring 1991)
- general MASnet functionality to the other resources at NCAR such as TAGS and IRJE (release planned spring 1991).

Integrated User Interface Development in the X Window System. This year SCD continued making X Window System applications available to as many different types of workstations as possible. SCD serves as a repository/library of X Window System software, including the development toolkits and Xlib. The division continues to consult on X Window Interface builders, to consult on X Window libraries and configuration issues, and to port useful client applications acquired from the "contrib" portion of the Massachusetts Institute of Technology (MIT) X Window distribution and from other sites using X Windows. SCD offers binaries for standard hardware platforms for X Window Systems versions X11R3 and X11R4, and for the application interface standards OSF Motif, Sun Open Look (OL), and the MIT distribution. As it becomes clearer that either Open Look or Motif is becoming the true industry standard, SCD will suggest to the users that they adopt it. SCD staff are experimenting with the first-time-user, graphical X Window Interface builders. They have started work on an X Window user interface for submitting asynchronous batch jobs. Having picked the IRJE facility as the first function to implement in the X Window batch interface, they plan to have a prototype running by October 1990.

Local-Area Networks and Communications

New high-speed networking technologies are emerging rapidly. For the most part, these are highly complex but are necessary in establishing the distributed computing environment demanded by NCAR scientists and users. Electronic mail systems and their information servers are also closely associated with networking. It is imperative that SCD remain abreast of the new networking technologies and standards for directory services that are fundamental to establishing a successful distributed computing environment.

SprintNet still provided access to the front-end computers at rates up to 2400 bps, but its use continued to decline. Use of the direct Wide Area Telecommunications Service (WATS) access at 9600 bps has leveled out; however, SCD continues to encourage users to access NCAR via the Internet/NSFNET.

The following projects were accomplished during FY 90:

- completed and gained acceptance of a general plan to provide high-speed communications between the Mesa Laboratory and the new NCAR North site using fiber optics
- continued to enhance the NCAR electronic mail system by consolidating all electronic mail databases into one centralized facility
- provided gateway service for Ellery Systems of Boulder (a NASA subcontractor) to access the Internet via NCAR in support of the NASA Science Network that has a node at NCAR.

Wide-Area Networks

During the past year, changes have continued to occur in wide-area networking at NCAR. The center continues to participate as a major hub for Internet traffic; also, new tools and services from the NSFNET Network Operations Center have come into existence, and new initiatives in national networking, in particular, the National Research Education Network (NREN), have been proposed that will impact or involve NCAR. Participation in the activities of the Internet Engineering Task Force and the Federation of American Research Networks (FARnet) has enhanced NCAR's role in the new initiatives.

Mexican Satellite Network Connection. NCAR supplied the initiative and staffing for the satellite link to the Mexican sites, Universidad Nacional Autonoma de Mexico (UNAM) and ITESM, and prepared a new site, Consejo Nacional de Ciencia y Tecnologia (CONACYT). This project is jointly funded by NSF's Division for Networking and Communications Research and Infrastructure (DNCRI) and NASA.

USAN. The primary regional network that SCD is involved with is the University Satellite Network. USAN continues to prove the efficacy of satellite transmission media for interactive access and file transfer services for users at member sites. USAN users can access NCAR and other resources on NSFNET and the rest of the Internet. The migration to full dynamic routing on USAN is complete. A statistics-gathering system has been installed. The full cost-recovery plan has been implemented.

Other Network Connections. Cooperative efforts with Los Alamos National Laboratory (LANL) resulted in the establishment of a 56-kilobits-per-second (Kbps) link between NCAR and Los Alamos. NCAR staff were also heavily involved in the establishment of a link between NCAR and the Boulder Laboratories of the Department of Commerce. Both sites now have gateway service onto NSFNET.

SPAN Support. SPAN is a NASA-sponsored, DECnet-based network with over 5000 nodes across the world. SCD provides centralized administration and support for the NCAR link to SPAN. SCD maintains a SPAN/Internet gateway to handle remote log-in, e-mail, and file transfers between the two networks.

BITNET/CREN. NCAR continued to maintain BITNET.

Gateways

MIGS provides MASnet access to remote systems that do not have a direct MASnet connection. Fully functional during FY 90, MIGS currently accesses remote systems with the file transfer protocol (FTP) or remote copy (RCP) file transfer utilities. Since MIGS requires a small amount of software to be resident on the remote system, it is distributed on a request basis.

Routine administrative updates and maintenance were performed on TAGS, and access to the new TAGS functionality was provided. The first version of the *MIGS User's Guide* was reworked into the comprehensive *MIGS Reference Manual.* New documentation produced include an *Introductory User's Guide* and a *Quick Reference Card.*

By mid-1990, MIGS was handling approximately 35,000 requests a month with 8 GB of associated data. A peak of 37,428 requests and 12 GB of data was reached in May 1990. Currently, 41 remote systems and 837 users are registered to use MIGS.

In the past, most of SCD's university users gained access to the supercomputing resources through a packet-switched, dial-up asynchronous facility provided by Telenet (now named SprintNet) and through a batch service called the Remote Spooling Communications Subsystem (RSCS). Use of RSCS has declined to virtually nothing, and it will be phased out. The IRJE system, which replaces RSCS, has seen high growth because of the increasing number of sites gaining access to the Internet and from the increased speed and reliability of the Internet that makes the transfer of multimegabyte files routine. The IRJE system was enhanced to include user access to the Mass Storage System, the Dicomed film recorders, and the Xerox laser printers. A more powerful computer was acquired for the IRJE functions, and those functions were moved to that machine.

Network Servers

SCD's network servers consist of the Mass Storage System and Text and Graphics Server.

Mass Storage

The NCAR Mass Storage System is designed for an environment dominated by supercomputers. It provides large archival storage and high-performance data access capabilities to supercomputers and a network of smaller machines serviced by MASnet. The NCAR MSS is patterned after the IEEE Computer Society Mass Storage System Reference Model and incorporates considerations that are unique to NCAR's computing facility. NCAR's environment demands that large amounts of data be moved at high rates between the MSS and its clients. A unique configuration of hardware and software is used to accomplish this task.

The NCAR MSS is designed as a closed archival system; that is, no user is allowed direct manipulation of data contained in the archive. Data are cataloged and formated in a method that allows the Master File Directory (MFD) to be completely rebuilt if any catastrophic failure occurs. A user may wish to remove or introduce data to the archives in a format not compatible with the one used by the MSS. To allow this capability, an import/export process is required. This process allows data to be introduced into the archives in almost any physical format used: 1/2-inch reel-to-reel tape, the newer 1/2-inch cartridge tape, and 8-mm helical-scan tape. Other devices may be used to provide access to the archive system as long as they match the IBM standard channel specifications. Currently, Small Computer System Interface (SCSI) standard devices, such as the 8-mm helical-scan tape, can be attached to the system via an adapter that is supplied by IPL systems.

The system is controlled by an IBM 3090-110J central processor operated under the IBM MVS/XA operating system. This processor provides access to 32 MB of central storage and 16 data channels that have an overall bandwidth of 72 MBps. Two separate disk systems attached to the processor serve as the mass storage MFD and as a disk farm. The MFD is physically isolated from the disk farm to prevent delays due to intensive data manipulation. A second level of storage is provided by the StorageTek ACS, which acts as a medium-access, high-speed storage system. The archival level of storage is provided by a set of manually operated IBM 3480 cartridge drives.

The NCAR MSS uses the ACS in a unique way. It is treated as a very large, medium-access disk farm that is assigned all bitfiles 30 MB or larger. No cartridges are directly removed from the ACS, only bitfiles. As bitfiles age and are not accessed, they are migrated from the ACS to archive storage on the manually mounted IBM 3480 cartridge drives. This procedure eliminates operator interaction with the ACS and provides a large-capacity file system with a capacity of more than 1 TB.

During FY 90, new software and hardware that provide new functions and improved service were introduced to MSS users.

Software. Software development for the MSS has continued to enhance service to the user community. During FY 89, several pieces of new hardware were introduced to the system. FY 90 has required work on software interfaces to facilitate the implementation of these subsystems. The addition of the Y-MP into the SCD computing facility, an upgrade of the LDN, and many user requirements for the MSS import/export facility have required intensive work for the MSS Group. Finally, two new software projects were initiated. The first will allow large data sets, in excess of 200 MB, to be written. The second will enable TCP/IP to be used to satisfy low-performance network data requirements.

A long-awaited upgrade to the Local Data Network was finally implemented. New controller adapters called Remote Device Modules with Extended capability (RDM-E) were made available from NSC. The protocol was modified from the current adapters, which required a rewrite of several software modules in the bitfile driver. These modifications have been made and are ready for installation.

Users have requested many specialized modifications be made to the MSS import/export facility. As of the end of FY 90, the external media facility of the MSS can process many of the most imaginative formats clients have been able to create. In addition, a facility to process many files to and from high-capacity media, such as the EXAbyte tapes, has been introduced and is functioning as specified by the Mass Storage Advisory Committee.

Hardware. Near the end of FY 89, two new hardware systems were purchased: the IPL 6860 SCSI adapter and the ACS. The IPL 6860 adapter provides an interface to an EXAbyte 8-mm helical-scan cartridge tape. This adapter allows the EXAbyte drive to be connected to an IBM mainframe block multiplex channel operating at a burst speed of 3 MBps. The drive itself is capable of sustaining 246 KBps. This systems allows the MSS access to 2.3 GB of data from a small cassette the size of a standard audio cassette. This subsystem was made generally available during the first quarter FY 90.

The ACS was introduced to the Mass Storage System in FY 89 to provide a medium-access, high-speed transfer, low-cost virtual disk system. This device was delivered with four StorageTek 4480 cartridge drives and nearly 6000 cartridges that provide over 1.1 TB of storage, with a nominal access time of 34 seconds, and a transfer rate of 24 Mbps. After the arrival of the ACS, data were no longer archived on half-inch tape. Actual use indicated that as the system was loaded to full capacity, more volumes were requested than the ACS was able to service optimally. After a study indicated that additional drives could improve this response, four more drives were added in early FY 90.

Text and Graphics Server

Under the generic name of Text and Graphics Server, SCD provides three major hardcopy systems: (1) the Dicomed Online Operating System (DOOS) MASnet server node, (2) the Xerox 4050 laser printers (on the MSS MASnet server node), and (3) the TAGS MASnet server node.

DOOS. The DOOS system drives the Dicomed black-and-white fiche and film cameras with NCAR pre-CGM and CGM formats as input. These cameras are currently shared with TAGS. From December 1989 through July 1990, DOOS averaged 510,408 images per month for both fiche and film formats.

Xerox 4050. The Xerox 4050 laser printers are currently attached to and driven by the MSS IBM 3090 controller. The input formats are ASCII text and NCAR CGM. The printers have the capability to perform duplex (two-sided) printing and to place multiple images on a page.

From December 1989 through July 1990, the Xerox 4050 printers averaged 286,333 images per month, of which approximately 13.1% were graphics images.

TAGS. TAGS is the replacement for the interim SUDOOS software. It is a UNIX-based output spooling and control system.

Currently, the only directly connected TAGS output devices are the Dicomed D48 fiche and film (black-and-white and color) recorders.

TAGS accepts, from MASnet, input files of the following formats:

- NCAR-formatted CGMs
- CGMs that adhere to ANSI X3.122-1986 CGM Part 3 (Binary Encoding) with limitations
- NCAR Raster Interchange Format (NRIF), both native and encapsulated
- ASCII text, both with and without Fortran carriage control characters.

TAGS has the ability to drive multiple output devices simultaneously. Support for large graphics jobs (such as movies) is provided since TAGS can automatically fetch data files stored on the MSS. A reference manual and several access documents were produced.

The TAGS phase 1 implementation was made available for general use during May 1990. Since then, the number of images produced by TAGS has nearly quadrupled to 90,565 for July 1990. This number is expected to rise sharply when DOOS is decommissioned in October 1990. Charging for TAGS services was initiated in August 1990.

Scientific Visualization

The term "scientific visualization" refers to the process by which scientists gain insight into problems using visual techniques. It implies a shift in emphasis away from computer graphics and toward the overall process of analysis. Scientific visualization tools leverage this process by unifying several technologies including, but not limited to, computer graphics, user interfaces, data management, artificial intelligence, and signal processing. Our plan is to provide a comprehensive set of state-of-the-art visualization capabilities to the UCAR/NCAR scientific community.

At present, NCAR Graphics is a set of predominantly two-dimensional graphical tools well suited for applications in the atmospheric and other geosciences. NCAR Graphics is primarily a subroutine library and, as such, has only minimal provisions for the user interface and data ingest. NCAR Graphics does, however, include tools for viewing graphical output that address the rapidly evolving user interface. The current release of NCAR Graphics extends the realm of two-dimensional graphics to a reasonable functional plateau. Future emphasis will continue to focus on the user interface, data interface, and a seamless fit into the modern desktop computing environment.

The next generation of visualization tools for NCAR will rely heavily on three-dimensional techniques coupled with animation in a distributed computing/supercomputing environment. The tools will, in most cases, not be programmatically used. The user interface will be window-based and easily as important as the visuals it allows one to create. The explosive growth in the area of scientific visualization will give rise to a diverse and rich set of tools available from many institutions. Commonality and interoperability will be key issues and probably the focus of much development work. Nonetheless, it is likely that certain capabilities somewhat unique to the geosciences will need to be developed. There are three-dimensional analogs to much of the functionality in NCAR Graphics; thus, techniques such as velocity vectors, streamlines, contouring, and mapping are all likely candidates for a migration to the world of temporal three-dimensional visualization.

The geosciences community is collecting and generating vast amounts of data that span the four dimensions of space and time. These data also include more than one variable. Thus, the ability to generate animation sequences showing time evolution or spatial translation and rotation of the scientific variables is essential to gaining insight into the contents of the data in a time frame that is in keeping with the rates at which the data are being collected. The computer and video technology necessary to create good-quality animation sequences of these data in a convenient manner is an expensive but shareable resource. As workstations become more powerful and less expensive, they are becoming more capable of effectively supporting this function. Consequently, video animation appears to be the preferred approach for the future. Video animation is also important to scientists for use in peer presentations, conferences, proposals, promotional efforts, and even increasingly for publications. Communication of animated sequences to a broader public, such as the broadcast media, is best accomplished using video media as well.

The Scientific Visualization Group (SVG) will assume a leadership role in technology evaluation for NCAR. This will lead to the development, acquisition, and installation of visualization tools and services that satisfy a complex set of requirements balancing function, cost, standards conformance, portability, supportability, and interoperability.

Charting a course in an area that is changing so rapidly is an exceedingly difficult task. In an attempt to unravel some of the complexity, the next section offers a "visualization architecture" that serves as a foundation for examining existing tools, how they are related, and possible evolutionary paths.

An Architecture for Visualization

Figure 6 shows a simplified visualization architecture that represents SVG's view of its anticipated future direction.

The user sits at a terminal or workstation that is an X Window System server and selects the NCAR interactive application. A top-level window appears and provides the user access to a number of tools including NCAR Graphics, the National Center for Supercomputing Applications (NCSA) tools, PolyPaint (graphics mapping/rendering software developed by staff

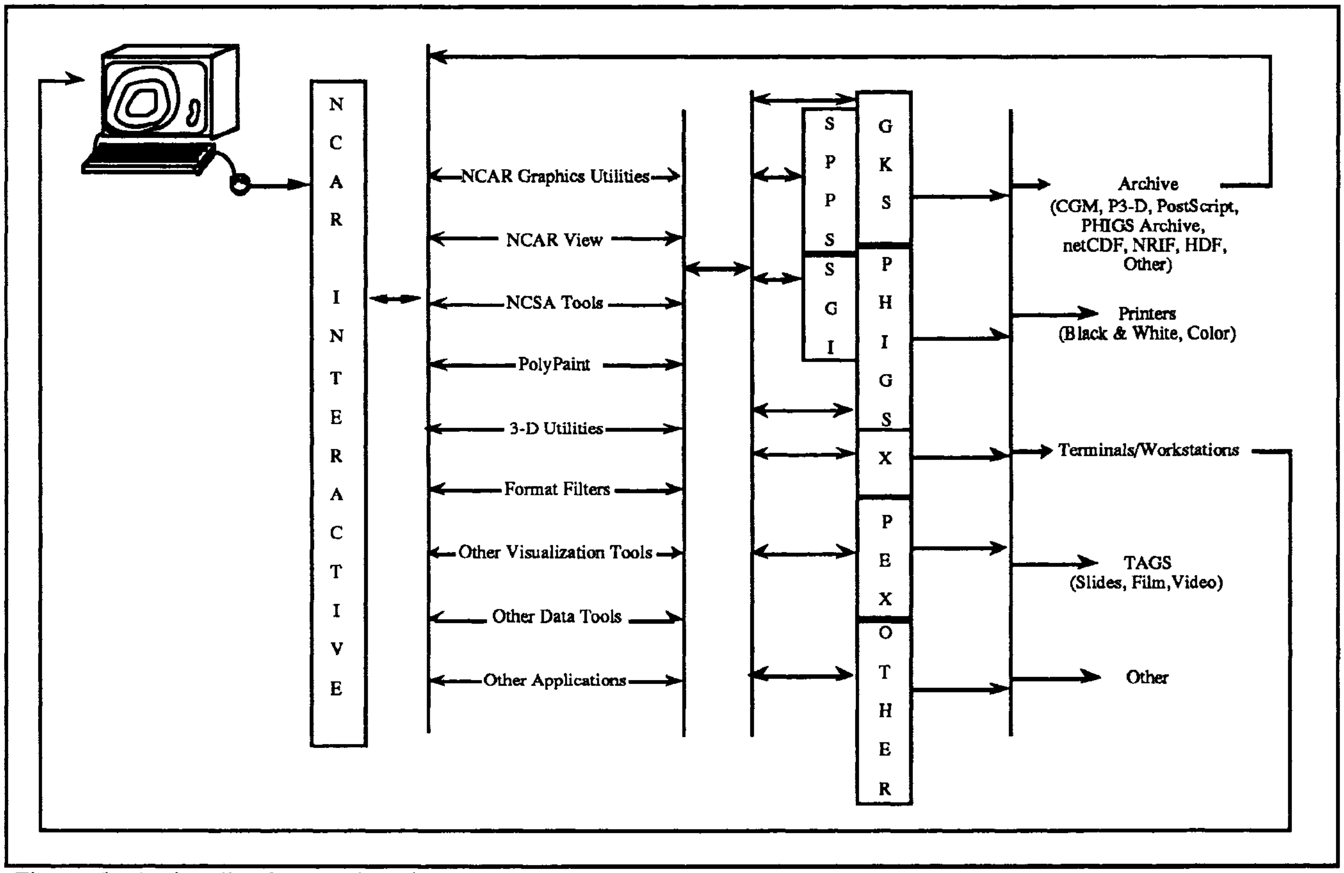

Figure 6. A visualization workstation.

in NCAR's Mesoscale and Microscale Meteorology Division), and others. The top-level interface will be easily extensible to allow the addition of new tools. All tools available through the top-level window have their own X Window System–based interactive interfaces.

Three minimization efforts are needed to constrain the complexity of this workstation environment: software selection, software standards, and archive formats.

Software Selection. The visualization and data-processing tools should be functionally complete, but not redundant. The SVG is currently reviewing visualization software and services that satisfy a complex set of requirements balancing function, cost, standards conformance, portability, supportability, and interoperability.

Software Standards. The number of underlying graphics standards should be as few as possible. To simplify the creation of a full visualization service based upon the integration of a variety of tools from a variety of sources, SCD remains committed to use standards whenever possible in all stages of the visualization cycle. Visualization tools that are written or acquired will adhere to programming language standards. Currently, Fortran 77 and C, as proposed by the American National Standards Institute (ANSI), are the popular choices in visualization software.

The X Window System has evolved as a very strong de facto standard for networked client/server applications. Applications can be executed on a client and the results can be displayed at the server. X Window System platforms can include supercomputers, workstations, and X Window terminals. Moreover, X Window System toolkits such as Athena, Motif, and XVIEW have become the de facto standard for interactive "point-and-click," window-based user interfaces. Current graphics standards include the two-dimensional GKS standard and the three-dimensional Programmer's Hierarchical Interactive Graphics System (PHIGS) standard that enables the rendering of images from three-dimensional structures. Thus, multiple views of a three-dimensional structure are more efficient to generate since creation of a next view need not return to a geometry-rendering stage. PHIGS functionality is being added to the X Window System through the development of PEX (PHIGS Extensions to X). The first public release of PEX is expected in late 1991.

Since the functionality of GKS is a subset of the functionality of PHIGS, one possible approach to reducing the number of underlying standards would be to convert any tools, such as the NCAR Graphics utilities, from dependency on GKS to dependency on PHIGS. SVG staff will investigate this possibility in FY 91.

Archive Formats. The netCDF utility was developed by the UCAR Unidata Project for use in a networked environment. It is a generalization of the NASA Common Data Format (CDF). Scientists will be encouraged to format their model output and observational data in netCDF to facilitate input of that data to processing and visualization tools.

Archive files generated by the visualization software will include raster images, encoded metafiles of two-dimensional vector images, and three-dimensional structures of graphical objects. For raster images, NRIF, developed in support of TAGS, will be adopted. The two-dimensional vector images will be in CGM format, which is a very strong, widely adopted standard. The standard format for three-dimensional structures is still too new to list here. However, PHIGS, which is a possible candidate, has an archive format for data structures. Also, the Pittsburgh Supercomputing Center has proposed an extended structure, called P3D, to the SLATEC Plotting Library Group. To avoid an excessive number of format filters, it is important for the visualization community to adopt as few archive formats as possible. The SVG has already developed numerous raster format filters because a strong standard has yet to emerge.

The Visualization Computing Environment

The Scientific Visualization Group had three major areas of research and development activity in FY 90: (1) complete Version 3.00 of NCAR Graphics and NCAR View; (2) investigate video animation capabilities for NCAR and university scientists; and (3) continue research and development of a visualization architecture in support of scientific research with Digital Equipment Corporation (DEC) as part of a Joint Research Project (JRP). The largest group activity in staff hours (approximately 60%) continued to be maintenance and support of NCAR Graphics and NCAR View.

Moderate areas of activity included continued collaboration with the SLATEC Graphics Group in building common graphics capabilities, support of the UCAR Foundation in establishing additional corporate sponsors and in technology transfer, participation in activities of the local NVUG, and sponsorship of a University of Colorado (CU) software engineering project in visualization.

Version 3.00 of NCAR Graphics/2-D

Version 3.00 of NCAR Graphics contains seven new utilities including CONPACK, PLOTCHAR (a text-writing package), SOFTFILL, COLCONV, GFLASH, LABELBAR, and STITLE. NCAR View Version 3.00 included an X11 driver, a Sunview driver, the Interactive Display Tool (IDT), and support for more output devices.

Video Animation. In FY 90, SCD worked with several NCAR scientific project staff to create a number of video productions using an optical disk–based animation system procured and integrated by SVG staff. The experience gained in this process helped to formulate a strategy for providing video production services for all of NCAR's scientists as well as SCD remote users.

Additional equipment for this purpose, acquired in FY 90, included a Sun SPARCstation/370, an Abekas A60 digital frame recorder, a Parallax video board, and a collection of videotape recorders and editing equipment. Integration work for this system began in FY 90, but will not be completed until well into FY 91.

System Installation, Integration, and Maintenance. A substantial number of visualization hardware and software projects were added, including:

- acquiring and installing a Sun-4/370 controller named *lonecone* for use with an Abekas A60 digital frame store. This system is used for SVG research and development, for scientific visualizations, and to prototype a TAGS video animation production system.
- obtaining and installing a DECstation 5000. A field test version of the Stardent AVS software, Digital PHIGS, and OSF Motif were added.
- acquiring, installing, and using X Window System Version 11 Release 4 and X image and X dataslice from NCSA, and testing a graphical user interface (GUI) builder for OSF Motif.

CU Student Project. The SVG sponsored the X11/Motif color editor project, XCOED, which is a stand-alone application meant for use with NCAR View and other graphics previewers.

Collaborations. SVG staff worked on the following collaborative projects:

- NCAR Graphics was supported on VAXstation ULTRIX and Reduced Instruction-Set Computer (RISC) DECstation ULTRIX systems. A laser disk–based interactive exhibit on global warming was created for the Association of Science-Technology Centers and the Franklin Institute Science Museum as a joint collaboration by the SVG, NCAR's Climate and Global Dynamics Division, DEC, and WaveFront Technologies Inc. A DECstation 5000 was acquired under the DEC JRP grant and installed for SVG use. SCD became a field test site for the Stardent Corporation AVS software. A first draft of the survey of visualization needs among NCAR staff and scientists was completed. Publication as an NCAR Technical Note is pending.
- SCD continued to support NCAR Graphics marketing ventures of the UCAR Foundation through meetings, presentations, demonstrations, and contributions of software and online documentation tapes.
- SCD continued to be active in the NVUG by participating in meetings, giving presentations, sharing software through the /VISTOOLS mass store directory, and disseminating information through the **visual@ncar.ucar.edu** news group.

Data Support

The Data Support Section (DSS) maintains a large, organized archive of computer-accessible research data that is made available to scientists around the world. The archive represents an irreplaceable store of observational data and analyses, and is used for major national and international atmospheric and oceanographic research projects.

There are now over 350 distinct data sets in the archive. The sets range in size from less than 1 megabyte to over a terabyte (TB). On 13 August 1990, DSS had a total of 61,335 bitfiles on the MSS with a total volume of 2.437 TB (19.5 Tb), an increase from 2.018 TB at the end of FY 89. This is 16.9% of the total MSS data and 11.7% of the bitfiles.

The DSS staff provide assistance and expertise in using the archive and help researchers locate data appropriate to their needs. Users may obtain copies of data on tape or use data directly on the NCAR Mass Storage System. DSS staff also assist scientists by providing data access programs (to read and unpack data) and other software for data manipulation, as well as a variety of written materials.

From October 1989 to August 1990, DSS staff handled many requests for information about data, data-processing tools, and online access programs. Staff handled 317 requests for data to be sent off-site. These requests required data from 424 data sets. Data were selected from 2913 tapes and mailed to users on 990 tapes. Many other people used the data online at NCAR.

Major tasks completed in FY 90 follow:

- DSS staff completed a project with the University of Washington to prepare a compact disk–read only memory (CD-ROM) with daily atmospheric analyses for several levels over the Northern Hemisphere. The starting dates were mainly 1945 or 1963 extending through June 1989. The CD-ROM became available in June 1990.

- Many scientists performing global assessment studies (such as EPA) are using NCAR's archive of climate model data. DSS is acting as the world model data center for these studies. This includes about 24 worldwide agriculture groups, 10 river flow teams, and several forestry studies. A very useful version of the climate model data with world coverage (not sectors) was completed in November 1989. New model data sets were made available. New texts describing the general circulation model runs were prepared.

- A new major archive (flux fields) from the National Meteorological Center was begun. This contains fields such as precipitation, radiation, stress, and clouds.

- New major advanced archives for 1985–89 started to arrive from the European Center for Medium-Range Weather Forecasts (ECMWF) in June 1990. As of 15 August 1990, about 114 of 275 tapes are at NCAR.

- DSS provided data support (satellite data) for a major NASA study on world temperature trends. NASA published global temperatures for 1979–88 based on satellite microwave data. NCAR extracted the data subset from TOVS (Thermal Infrared Observational Satellite Observational Vertical Sounder), a very large data set.

- Ocean modeling efforts at NCAR rely on the DSS to derive and provide climatic and time series of in-situ and remotely sensed data. The section continued to provide data of this nature, through the Comprehensive Ocean-Atmosphere Data Set (COADS) and other ancillary data sets that serve as initial conditions during the model run, and verification and comparison analyses following the simulation. For climate models to be more realistic, ocean models must assimilate data in the same spirit as atmospheric models. Modern data sets are acquired as needed. DSS staff made these data sets (such as Geodesy Satellite [GEOSAT] altimeter measurements) readily available to ocean model researchers, focusing primarily on the data assimilation technique without the burden of developing data-handling methods.

  A new sea surface wind stress climatology, illustrating the importance of global data sets for climate research, was derived from ECMWF analyses and was distributed to more than 20 research centers throughout the world.

- DSS staff developed plans to make possible a future reanalysis of the global atmosphere. This will be a huge project and very useful for world science.

- The staff participated in several international data exchanges. Formal U.S.-USSR data exchanges were very active during 1990. Several data sets have been exchanged under each program. For example, NCAR received 12 million ship observations from the USSR during 1989–90 and expects 8 million more by November 1990. This will increase the volume of COADS input data by about 20%.

- Four more detailed inventories were prepared for online accessibility. A total of 21 inventories, including several types of surface, upper air, and satellite data sets, are now available. In addition, DSS staff completed an update of Australian upper-air (rawinsonde) data.

Operations and Plant Engineering

The SCD Operations and Maintenance Section is responsible for the continuous operation of the NCAR computer center and keeping it in first-rate condition. The operations staff are present 24 hours a day, 365 days each year. They control the traffic flowing through the "electronic highways" of networks that represent both incoming calculations to be processed and the various forms of output that represent terminal graphics, black-and-white or color film and slides, data to be transferred back to the user, and data to be archived on the NCAR Mass Storage System. They are also responsible for monitoring the many electrical and mechanical subsystems required to support the needs of a supercomputer center. Operations staff can assist users with operational questions during the evenings and weekends when User Services staff are not available.

Maintenance of computing equipment and associated peripherals is performed by contracted vendor staff or in-house engineers. The Maintenance Group performs continuous maintenance for the Dicomed film processors including the cameras and disk drives; the Gandalf Dual PACX IV port contention device; all communications connections, nodes, and hardware; and approximately 700 NCAR PCs and workstations.

The Maintenance Group is available to fix almost anything electric or electronic in the NCAR inventory of equipment. The group schedules training and recertification courses. The operations staff assist the Maintenance Group by contracting for maintenance on the micro- and minicomputers, the Cray, IBM, and Xerox equipment.

Operational Summary

One way of measuring the operational potential of the SCD computing center is through statistics. SCD's FY 90 operational statistical highlights are delineated below:

- an average of 70,000 cartridges were manually mounted per month

- an average of 250,000 pages of printer output were generated per month

- an average of 500,000 fiche frames were produced per month

- an average of 100,000, 35-mm frames were produced per month.

Computer Center Space Requirements

During FY 90, 14,616 IBM 3480 tape cartridges were added to the MSS inventory, bringing the total to 81,208 tape cartridges. Mass storage growth continues to closely follow the FY 87 projections. The SCD computer center can store a total of 121,000 cartridges in its present configuration.

Utilities

A review of facility and physical plant elements would be incomplete without mentioning that the installation of the IBM 3090 mass storage control processor and the CRAY Y-MP8/864 required extensive modifications to the electrical and air conditioning systems. It must be noted that it would not have been possible without the cooperation and efforts of the SCD staff, the NCAR Facilities and Support Services section staff, and the Cray engineers.

Electricity. The 125,000-volt amperes (KVA) of UPS power installed in FY 89 has been put into action and now supports the Xerox laser printers, the film room including the Dicomed cameras, the IBM 3480 tape cartridge readers and controllers, and the IBM 3090.

SCD maintenance staff designed a method by which the UPS system can also support the switching capability of the unit switch that coordinates the two main electrical feeders. These feeders each carry around 12 KV of power and require battery backup to drive the switch. The UPS system now supplies filtered and continuous power to keep the batteries at full charge, thereby extending their life.

The FSS staff purchased an electrical power monitoring device and began to create a database of information that shows the actual power consumption of our circuits as well as ground load information and noise. This will prove valuable in controlling our grounding grid and calculating the actual power draw versus the perceived power requirements as conceived by the manufacturer. There is often a big difference.

Air Conditioning. The STOLZ CompTrol 2000 unit, installed as a replacement for the oldest Liebert air handler, has performed well. It is more efficient at creating humidity than the existing Liebert units, and replacement parts are common and available locally.

Communications. The major project for the SCD maintenance group in FY 90 was the design of communications for the NCAR North building. Maintenance staff developed a design that places in each office enough wire to provide growth to include several network and phone-type connections, as well as two ethernet ports. Experience has shown that if this is not installed in the beginning, it will have to be added piecemeal at a much greater expense later. SCD maintenance staff are working with the NCAR North building architects and engineers to help this project to completion.

Operations staff found eight NSC HYPERchannel adapters on the GSA Surplus List and arranged for their transfer from the Red River Army Arsenal in Texas to the NCAR inventory. The shipment also included three adapter racks. This gives SCD some spares and permits an increase in network connections without substantial expense.

Computer Center Environment. Staff added many more sensors to the Anatel Environmental Monitor, which was installed last year. The unit has proved invaluable in notifying the staff when temperatures, water flow, humidity, chilled water, and so forth, approached preset limits. To date, this advance notification has allowed the maintenance group to react to and correct problems that would have caused computer center shutdowns in 12 cases. We added so many sensors that we had to upgrade the size of the hard disk to record all the information being gathered. The FSS staff added their own measuring sensors to our system to monitor devices critical to the computer center. The AEM is a good tool and the FSS staff plan to install an additional unit in the NCAR North facility.

Using a Macintosh running HyperCard, the maintenance staff created SCID, which contains a catalog of all wire connections and equipment layouts for the entire computer center and SCD office space. All equipment moves are recorded in this database. It provides information on configurations and machine connectivity and has been an invaluable resource.

User Services

As the central contact for the user community, the User Services Section delivers an integrated program of information services and software tools designed to assist the user in a complex supercomputing environment.

User Services' goals are to increase user productivity, identify user communities and their differing needs, improve communications between the user community and SCD, improve service levels, improve the quality of information services and software tools, expand the functionality of software tools, and increase the cost-effective use of computing resources. This is achieved through five functional areas within User Services: User Information, Documentation, Consulting, Training, and Software Libraries.

During FY 90, User Services staff focused on issues related to the COS-to-UNICOS conversion. They worked to keep users informed about the rapidly changing UNICOS environment, first on the CRAY X-MP/18 and then on the CRAY Y-MP8/864. They tested and documented conversion methodology for the users, utilities to use in conversion, and scripts to submit and control jobs in the UNICOS environment.

User Information

User Information staff facilitate the timely transfer of information from SCD to users, visitors to the supercomputing facilities, and the public. This is accomplished through a variety of online information services, telephone and in-person contact with users, and public displays and exhibits. User Information staff also enhance information exchange within User Services, collaborating with the Documentation and Software Libraries groups and the Consulting Office.

This year, User Information staff played a large part in the dissemination of information to users converting from COS to UNICOS. User Information staff interviewed users to determine documentation and SCD classes that would be most appropriate for their needs. User Information staff also played a major role in the Site Liaison Workshop, from conference design and organization to the setup and support of the hands-on computer laboratory and informational presentations.

With the rapidly changing supercomputing environment this year, users needed (perhaps more than ever) to be kept abreast of changes that would affect their computing. User Information staff accomplished this task largely by researching and coordinating *Daily Bulletin* news items from SCD's Systems, Operations and Maintenance, and Distributed Computing sections. Groups of users were also targeted to receive special electronic and paper mailings. As an example, over 630 active users who had not yet applied for an account on the CRAY Y-MP received applications via e-mail. Two months later, this was followed by a paper mailing to 241 active COS users who had still not requested an account on the Y-MP.

User Information staff continued to provide several valuable services in effect from last year: the *Daily Bulletin*, change control, new user calls, lost-job calls, and NCAR Graphics package information.

The *Daily Bulletin*, an online source of information about the computing environment published Monday through Friday, continued to be an invaluable tool for distributing time-critical information to over 1200 users. As a result, users had a single source of information that kept them up to date on matters that could not wait for the monthly newsletter.

New users continued to receive follow-up calls shortly after establishing their accounts on SCD's computers. Staff checked that they were reaching the facilities without difficulty, told users about appropriate training classes, and sent needed documentation.

Change control procedures, coordinated by User Information staff, were used to notify SCD system administrators and other SCD staff in advance of changes in software and hardware that might affect them and others in their group. It not only helped coordinate information dissemination, but also allowed for feedback on the proposed change, and helped track potential problems that can result from such modifications. As a result, change control continues to enhance the quality and reliability of SCD services and hardware and software supported by SCD.

The information and ordering materials for NCAR Graphics, Version 3.00, benefited from a major facelift and reorganization. Staff redesigned the materials to include answers to the most commonly asked questions to produce an effective marketing tool. A new color brochure demonstrating package capabilities completed the information packet. More than 1300 packets were sent to users with Version 1.00 or Version 2.*xx* of NCAR Graphics. Since then, an average of 90 packets per month has been sent to interested universities, government agencies, and for-profit companies.

User Information staff continued to be the central contact for providing graphics information, handling graphics distribution requests, answering availability questions, tracking the status of orders, assisting in installation questions, and implementing and maintaining the log file that documents contacts. Staff answered many other technical questions ranging from computer access and file transfer to UNIX and Microsoft-Disk Operating System (MS-DOS) operating systems. They also helped coordinate user efforts to evaluate AIX as an operating system for the IBM 4381 front-end computer.

The User Reference Library in the Consulting Office and SCD User Area (Mesa Laboratory) received a major update this year, as UNICOS documentation was phased in and COS documentation was phased out. It also grew in the number of available UNIX reference books. A complete listing of software reference materials available in the Consulting Office User Reference Library is now online.

Visitors and NCAR staff used the SCD User Area heavily this year, accessing SCD's supercomputing facilities and users' local computers, producing papers, transferring files to and from mainframes and PCs, and taking advantage of available software on the IBM PCs and Macintosh SEs. Terminal hardware and software in the SCD User Area were maintained throughout the year, and staff supported use of the licensed software.

SCDUG met monthly during the year. SCD regularly updated attendees on the latest supercomputing developments and requested feedback on new and planned hardware and software development. Special meetings were held on UNICOS and charging on the Y-MP. Site Liaison Workshop participants were invited to the special meeting on charging. SCDUG also coordinated a project to evaluate AIX through a friendly user testing program on the IBM 4381 front-end computer. In support of this project, User Information staff helped users with documentation and access questions, and coordinated the passing of information and feedback among SCDUG, the SCD consultants, and friendly users.

The Scientific Computing Division and NCAR gained new visibility this year with the creation of several new public relations tools: the SCD/NCAR exhibit, visitor's brochure, and public displays in front of the computer room.

An exhibit displaying SCD's technical collaborations with industry and the capabilities of the NCAR Graphics Version 3.00 package traveled to five conferences this year: Supercomputing '89 (Reno, Nevada), Supercomputing Europe '90 (London, England), the American Meteorological Society annual meeting (Anaheim, California), Supercomputing Japan '90 (Tokyo, Japan), and the Rocky Mountain Technology Transfer Conference (Denver, Colorado). Ordering information for the NCAR Graphics package and various SCD and NCAR documents was distributed widely to conference attendees. Increased interest in NCAR Graphics was observed after each trip. Four new topics that will update the information on the display panels for next year were developed.

Visitors to NCAR learned about NCAR's innovative partnership for weather and climate research from the new visitor's brochure. Readers were treated to a colorful explanation of the interactions between science and supercomputers, and researchers and networking.

The public displays in front of the computer room, developed last year, were updated to include relevant information about the new CRAY Y-MP8/864 computer and the StorageTek Automatic Cartridge System.

SCD's "application of technology on behalf of society" was documented in a short, five-minute videotape. Emphasizing SCD's innovation in the area of mass storage systems, the tape won NCAR one of the five finalist spots for the Environment, Energy, and Agriculture category of the national *Computerworld* Smithsonian Award.

Documentation

SCD documentation is aimed at helping users navigate in a heavily networked, multisystem environment. Although the division makes extensive use of vendor documentation for the supercomputers, mainframes, and workstations, this alone is not sufficient. Thus, SCD provides nearly 100 user documents, free of charge, that provide step-by-step tutorials, describe new software developed by SCD, and document local system modifications that affect users. Because SCD is evolving toward UNIX as the operating system for all its computers, it expects user documentation and software interfaces to become more uniform and hence simpler to both document and understand. The goal will continue to be to keep users apprised with timely yet accurate information, especially during the conversion period from COS to UNICOS.

Documentation accomplishments for FY 90 are listed below:

- The Documentation Group produced two versions of the *COS-UNICOS Conversion Guide* (125 pages) and two draft versions of the *NCAR UNICOS Primer*. These were both major efforts. The *NCAR UNICOS Primer* is aimed at getting users off to a quick start with the new UNICOS operating system. The *COS-UNICOS Conversion Guide* offers comparisons of common COS and UNICOS job scripts and describes useful UNICOS tools and commands.

- The January *SCD Computing News* was a special color issue, with articles and images describing Version 3.00 of the NCAR Graphics package. The Documentation Group produced two special issues of *SCD Computing News* that emphasized plans for the arrival of the CRAY Y-MP8/864 running UNICOS. The February issue consisted entirely of articles describing how to convert from COS to UNICOS, and the July/August issue contained many articles emphasizing use of the new Y-MP after its arrival at NCAR.

- FY 90 saw a big jump in the number and amount of online documentation provided on SCD systems. There are currently 26 user documents online—either via anonymous FTP on *windom* or via the **hints** command on shavano (CRAY Y-MP8/864). The Documentation Group has rearranged the topical order of its hardcopy UserDocs to make them easier to read when converted to an online presentation. The SCD User Documentation Catalog is also available online.

  The Distributed Software Libraries (DSL) utility provides online documentation for software libraries on the Cray supercomputer; hardcopy versions are located in the User Reference Library of the Consulting Office.

- Supercomputing centers face common problems of delivering online information in a heterogeneous computing environment and the lack of vendor solutions that work in diverse computing environments for diverse types of documentation. With changing technology, the time appeared right to make substantial progress on developing a widely available online documentation system. Thus, NCAR and LANL co-organized and hosted the Workshop on Online Documentation in the Supercomputing Environment, which took an in-depth look at the state of the art of online documentation at the major U.S. supercomputing centers. Participants included writer/editors, software librarians, and distributed computing specialists from 12 leading supercomputing sites, including the national DOE laboratories, National Institute of Standards and Technology, the NSF supercomputing centers, university and regional supercomputing centers, Cray Research, and IBM. Seven SCD staff attended. Following the workshop, SCD collaborated with LANL to produce a working paper containing workshop results and recommendations for the future. A steering committee was formed to continue progress toward an online documentation system for the supercomputing environment.

- In November 1989, SCD hosted the Sixth DOE Forum on Computer Systems for Documentation in Estes Park, Colorado. The conference was attended by 53 representatives from 17 large, government-sponsored laboratories. This group of managers, programmers, and writers exchanged ideas through open forum discussions and formal presentations that focused on the theme "Tomorrow's Documents with Today's Technology."

- SCD participated in the beta testing and friendly user review of the new Text and Graphics System. This was a major project for which the Documentation Group generated many draft versions of documentation as the system development evolved.

Documentation Projects. In FY 90, the Documentation Group produced 69 new versions of 37 hardcopy documents. Seventeen documents were rewritten and released more than once as new information became available. Another five documents were reformatted for use online. Each document covered a specific limited topic, and they had an average length of 27 pages. Two major manuals (*NCAR Graphics Guide to New Utilities* and *NCAR UNICOS Primer*) were 500 and 440 pages long, respectively.

Graphics Documentation. In the first quarter of FY 90, NCAR released Version 3.00 of the NCAR Graphics package. The Documentation Group completed the reference manual and several other associated documents and assisted in the design and preparation of an extensive information packet containing a color brochure, licensing information, order forms, and information sheets. The packet was used for marketing the product to potential users.

Between January and July 1990, 272 NCAR Graphics generic packages were distributed. Documentation for the package includes *NCAR Graphics Guide to New Utilities, Version 3.00; NCAR View: A CGM Translation and Manipulation Package* (NCAR View Version 3.00); *The NCAR Graphics Installer's Guide; AUTOGRAPH: A Graphing Utility* (reprinted); and *NCAR*

Graphics User's Guide, Version 2.00 (reprinted). An additional 669 copies of the *Guide to New Utilities* and 520 copies of the *User Guide* were also distributed.

Newsletter. During FY 90, the group produced 11 issues of *SCD Computing News*. Two writer/editors served terms as managing editor of the newsletter, enabling the group to better keep pace with the news. Because average issue length had crept up from 28 to 35 pages, the Documentation Group surveyed users about the usefulness of some of the back matter, such as indexes and SCDUG minutes. As a result, they moved the index and SCDUG minutes online and dispensed with the lists of acronyms and allocated computer resources. Since this reorganization, average page length for news issues has been 24 pages.

Consulting

The Consulting Group provides a centralized forum for resolving time-critical user problems, advising users on optimal programming techniques, recommending documentation on SCD's computing facilities, and channeling user needs into the planning process. In addition, consulting services are provided by other groups within SCD based on referrals by the Consulting Group and by direct user contact.

The general goals for the Consulting Group are to:

- sustain a high level of technical expertise and support to ensure that user inquiries and needs are responded to and met in an accurate, timely, and amicable manner

- explore and develop various methods of increasing the user's basic knowledge in all aspects of SCD's computing environment

- strive to enhance communications among the consulting staff, users, and SCD management.

FY 90 was a year that expanded the base of knowledge among the consulting staff. An average of 750 user contacts per month were made by the Consulting Office in FY 90; this is up from an average of 450 in FY 89. A contact is defined as a user consultation with a member of the consulting staff, whether by phone, by e-mail, or in person. One contact may involve more than one question and may require additional research and follow-up.

To prepare users for the important conversion tasks awaiting them, the Consulting Office staff worked diligently to make critical documents ready on time; to prepare and present classes to learn new utilities, to further assist users with conversion problems, and to test new software.

Continued Consulting Services. Consulting was provided in the following areas: COS, UNIX, UNICOS, VM/SP and CMS, Cray and IBM Fortran, Mass Storage System, MASnet, MIMPORT/MEXPORT, input/output, mathematical and statistical software, networking, data communications, terminal emulator software for IBM PCs and Apple Macintosh computers, X Window System software and usage, NCAR Graphics software, movie production, Cray vectorization and optimization, and COS-to-UNICOS conversion.

Much of the documentation produced by User Services was written and reviewed by Consulting Office staff. Technical examples for new documentation were provided after thorough testing by the consultants. In addition, each month consultants wrote the "Hints from the Consultants" section of *SCD Computing News* as well as other feature articles.

Extended Support Services. The staff continued to test software before its general release to users. This included software such as MIMPORT/MEXPORT, LREAD/LWRITE, AIX on the IBM, NCAR Graphics, the X Window System, MIGS, TAGS, and IRJE interfaces. This type of testing not only resulted in the release of adequately tested software, but it increased the level of interaction between consultants and other SCD staff.

Staff completed support for the EPA Acid Rain study, which included managing the overall technical coordination of the project, collaborating with EPA on a variety of issues, addressing connectivity issues such as monitoring links and testing file transfers, testing software written explicitly for this project, and consulting on the Statistical Analysis System (SAS) and related usage particulars.

User Services staff participated in planning and coordinating the 1990 Site Liaison Workshop. The Consulting Office staff prepared and presented 15 of the 23 technical talks for the workshop.

Record Keeping and Reports. Consulting logs were maintained throughout the year, and a new, easier form was developed for logging contacts. The Graphics database continued to grow as the GKS package was distributed. It was used by the consultants to determine whether the user contacting the Consulting Office with questions was an official site representative for NCAR Graphics.

Training

Training is provided to increase users' skills and knowledge about SCD's computing resources. This reduces their need for troubleshooting assistance and increases their ability to extract additional computing power from the NCAR computing environment. Course development and presentation are provided by the Consulting Group.

New levels of training attained the previous year were maintained. The 1990 Site Liaison Workshop was held and training in UNIX, UNICOS, and conversion was provided to users.

A UNICOS orientation class was developed and then offered at NCAR to local and remote users using a lecture/hands-on format. This is a two-and-a-half-day class based on the new *NCAR UNICOS Primer*. In most instances, users felt the class was extremely beneficial in helping them begin computing in the new SCD environment.

A conversion class for COS users was developed and taught on a regular basis to help people get started on the road to UNICOS. This class was designed to address two audiences: those who know UNIX (one-day class) and those who do not (two-day class).

The Site Liaison Workshop was held on 24–29 June 1990 and was attended by approximately 40 participants, predominantly from universities. This workshop centered around the issues of converting from COS to UNICOS. UNICOS tools, CFT77 issues, autotasking, NCAR Graphics conversion, and MSS commands on UNICOS were just some of the topics addressed at the workshop.

The Consulting Office videotape library now contains over 14 training tapes for UNIX, PC SAS, and selected Macintosh applications software. Messages were sent to staff via electronic mail and articles were submitted to *Staff Notes,* advertising videotape availability and encouraging their use.

Software Libraries

User Services staff support a growing collection of quality software packages, based on recommendations from users and colleagues within NCAR and at other computing centers. These packages meet user needs for functionality on both central and distributed systems in the areas of mathematics, statistics, user interfaces, and general utilities. The staff also provide limited design and development of user interfaces and utilities.

Software Libraries staff participated in the newly formed Database Advisory Committee to assist and advise on a common management system on various NCAR computers. They assisted users with the COS-to-UNICOS conversion by consulting on UNICOS utilities and library software, I/O, and data transfer between UNICOS and other UNIX computers. They expanded the DSL utility to include the following large libraries: Numerical Algorithms Group, Inc., International Mathematical and Statistical Library, and SLATEC. They installed graphics and mathematical libraries on the UNICOS CRAY X-MP/18, and later on the Y-MP8/864, with UNIX makefiles developed during FY 90. The staff consulted on Cray software questions, not specific to UNICOS, averaging six questions per week. They obtained version 2.0 of LAPACK from Oak Ridge National Laboratory, which provides parallel processing functionality for EISPACK and LINPACK operations on low-end parallel computers. The library was installed on the Y-MP and tested as part of NCAR's participation in the LAPACK effort.

Software Libraries staff represented NCAR at one SLATEC Common Math Library meeting. During this meeting, they answered questions about NCAR-contributed libraries FFTPACK and FISHPAK. Software was maintained on COS and the UNICOS Y-MP8/864, an effort that included regenerating the software under CFT and CFT77, and also applying critical fixes to the software. The CRAYFISHPAK library was installed on the Y-MP8/864 and this library's documentation and test files were added to DSL.

Computational Support

The Computational Support Section (CSS) provides state-of-the-art expertise in aspects of computing that are beneficial to the atmospheric and oceanic sciences communities. This expertise is communicated via consulting, publications, software development, and training. Performance monitoring and benchmarking studies are conducted to ensure the efficient use of the current computing resource and to aid in selecting the most appropriate future computers. The section also processes all university requests for computing resources and plays an active role in the Fortran standards effort.

Allocation of Resources

The section is responsible for selecting reviewers for computing resources requests, updating the reviewer database, and presenting computing requests for more than 100 GAUs to the SCD Advisory Panel at its biannual meetings. Smaller requests are handled by the CSS based on peer review.

In the past year, 199 requests were approved for a total of 12,432 GAUs. Processing these requests involved soliciting opinions from over 300 reviewers in all areas of atmospheric science. In addition, support was provided for university classroom projects in meteorology. Thirty-three students from five universities were given access to supercomputing at NCAR.

CHAMMP Interagency Organization for Numerical Simulation (CHAMMPions)

This research project is intended to provide the technological advances required to support the development of an atmospheric circulation simulation system on parallel supercomputers. The project is one component of an effort to develop an advanced climate model with throughput capability significantly greater than that of current models. Such an effort is required to accelerate the identification, evaluation, and implementation of long-range energy policies that may be needed to improve the global standard of living while assuring environmental quality. An interdisciplinary team at Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), and NCAR will be established, and the teams will jointly perform research in three related areas: advanced numerical methods, model development, and parallel software tools. NCAR's team members are from SCD's Computational Support Section and CGD.

In addition, the project will sponsor interdisciplinary, interagency workshops. These four activities will lead to the development of advanced numerical techniques and improved climate representation suitable for distributed-memory, parallel computers. The results of the project will be made available to the research community via research papers, parallel algorithm libraries, software tools, and parallel implementations of atmospheric circulation models.

In FY90, six meetings or exchanges took place in support of the CHAMMP project including two at NCAR.

Numerical Methods and Parallel Algorithm Development. Work began on parallel implementations of three existing methods in prototypes for Multiple-Instruction Multiple-Data (MIMD) and Single-Instruction Multiple-Data (SIMD) machines. Both MIMD and SIMD computers were examined in this project to determine the suitability of either class of parallel computers for the possible coupling of the atmospheric model with other components of the global climate system being examined by other projects. The aim of this work was to evaluate the suitability of these methods for large-scale parallel execution. The spectral method, finite difference method, and a composite mesh finite difference method were applied to the nonlinear shallow water equations on the sphere.

Working Parallel Atmospheric Model. The Computational Support Section has developed a series of models to evaluate the suitability of various methods for solving the nonlinear shallow water equations on the massively parallel Connection Machine 2 (CM-2). In FY 89, a finite-difference, grid-point method and the pseudo-spectral methods were implemented. Two of the models achieved execution rates of 1.7 and 1.2 Gflops respectively.

In FY 90, a third version of the model was developed for the CM-2 that uses the spherical harmonic transform method of solution. This model is based on one developed by CGD for the CRAY X-MP and was extensively modified for implementation on the CM-2. The spherical harmonic transform method is widely used in atmospheric models and has global communications requirements that test the performance of massively parallel architectures. Preliminary testing of the kernel operations for this method indicate that this model will execute at up to two to three Gflops with the use of lower-level optimized utilities.

Moving the prototype onto the sphere is the beginning of a major step in the process of implementing the community climate model 2 (CCM2) on a multiprocessor system. It required the selection of data structures and algorithms that minimize the communication for the spherical harmonic transform. This transform dominates the computing time and its implementation, and, together with the fast Fourier transform (FFT), also provides a utility that can be used by the CCM2. The parallel computational algorithms for the harmonic transform are well known, but perhaps less important than the parallel communication algorithms that are currently being developed, since communication may dominate the total computing time.

Performance and Benchmarking

CSS staff are responsible for providing SCD management with information on the efficiency of use of current equipment and projections of the power of machines that are candidates for acquisition.

With the acquisition of the CRAY Y-MP and the change to the UNICOS operating system, the new job scheduler was studied and a series of tests were conducted to study the effect of various parameters on machine utilization and job throughput. In particular, the effect of a job's "nice" priority value on its throughput was studied. Nice value is the priority assigned to a job by the operating system. The higher the priority, the lower the nice value.

New computer systems are benchmarked routinely by the CSS. The benchmark set includes a simple two-dimensional shallow water equations model and a complex three-dimensional climate model. The shallow water model is a highly vectorizable and parallelizable code that gives an indication of high-end performance of computers on certain atmospheric problems. The climate model is a portable version of an early code of the CCM (Version 0B). A large fraction of the execution time of this model is spent on the parameterization of physical processes, which is a scalar process; it is also an out-of-memory model and, therefore, uses the external storage resources of a system. This model is an excellent test of the overall (vector, scalar, and I/O) capabilities of a computer system.

These benchmarks were run on a number of state-of-the-art computers that are available to the research community. Systems benchmarked include the NCAR CRAY Y-MP, the IBM RS6000 320 and 530 models, the Sun-4/490, and the DEC 5000. In addition, the benchmarks were sent to Fujitsu and Floating Point Systems for evaluation of their newest systems.

Software

MUDPACK. A package of portable vectorized Fortran subprograms for automatically discretizing and solving two- and three-dimensional real and complex linear elliptic partial differential equations (PDEs) using multigrid iteration has been developed. Boundary conditions can be any combination of periodic, mixed derivative, or Dirichlet. The solution region must be a rectangle in two dimensions or a box in three dimensions. The multigrid iteration can include Gauss-Seidel point relaxation, any combination of line relaxations, or planar relaxation (in three dimensions only). All methods use red/black ordering for vectorization and convergence improvement. Second-order finite differencing is used to discretize the PDEs.

MUDPACK has undergone expansion and improvement requiring a substantial recoding effort. Version 2.0 of MUDPACK now includes over 70 files (the original version included 45 files). The most important changes implemented during FY 90 were:

- the inclusion of multigrid options that set the number of pre- and postcoarse-grid correction relaxation sweeps, the kind of cycling (V,W, F or more general), linear or cubic prolongation, and half- or full-weighting with residual restrictions. This allows users familiar with multigrid iteration the opportunity to experiment with and fine-tune the underlying algorithms for greater efficiency. A new set of default options, chosen for robustness, is included for those preferring "black box solvers."

- the opportunity to use the "EQUIVALENCE" statement more with work space, right-hand side, and solution arrays. This is especially important with three-dimensional PDEs where central memory is easily exhausted.

- documentation improvements and standardization.

- the implementation of new access of the software documentation and test codes using the DSL utility. The solvers are now available in relocatable binary form.

- the introduction of a new user document for Version 2.0 of MUDPACK, which includes an expanded set of examples measuring MUDPACK software performance on the NCAR

CRAY X-MP (for example, Mflop rates and performance with various multigrid options are included).

A two-hour MUDPACK software lecture was given at the Multigrid Short Course at the University of Colorado in Denver.

MUDPACK documentation and software were distributed (usually electronically via the FTP utility) to 39 people throughout the research community. Additionally, MUDPACK binary libraries were set up at the University of Pittsburgh Supercomputing Center, the San Diego Supercomputing Center, and the National Center for Supercomputing Applications (University of Illinois at Urbana-Champaign).

An optimized multigrid code for solving a doubly periodic Laplace's equation on the unit square was produced as part of CGD's investigation into using multigrid with ocean modeling. The result was a code able to produce a discretization level error solution on a 1025 x 1025 grid in 0.35 seconds with a 100-Mflop rate. The code was compared with FFT and turned over to a consultant from the University of Colorado at Denver working for CGD.

Two-dimensional MUDPACK solvers have been included in an ocean model that is being distributed among various oceanographers.

Standards

The value of standards is well recognized in the scientific community where codes must be ported between machines from different vendors. For this reason, the CSS has played an active role in the Fortran 90 standards effort.

The CSS continues its participation in the ANSI Fortran Standards Committee (X3J3), as well as the international group of Fortran Experts (WG5) under the International Standards Organization (ISO). This year, the draft standard (Fortran 90) was accepted by the international Fortran Experts Group. Numerous editorial changes were made to the document at their suggestion.

An effort is being made to synchronize the completion of the ANSI standard with the ISO standard. Therefore, a third public review of the draft is planned for September and October in the United States to be finished when the ISO vote is complete. The second public review responses are now being written by the committee.

A *Programmers Guide to Fortran 90* was published in April 1990. A handbook, which is an attempt to write the Fortran 90 guide in "ordinary English," is planned for next spring.

Research

Research is a key effort in the Computational Support Section. Currently, research is being conducted on the multigrid algorithm for solving elliptic equations, on the implementation of fluid dynamical models on massively parallel processors, and on partial differential equations in computational fluids, is being conducted.

John Adams has developed MUDPACK (see description under "Software"). The package, which will vectorize on Cray computers, is easy to use, efficient, and can be applied to a wide range of problems.

The "reduced" system of equations commonly used to describe the time evolution of the polar wind and multiconstituent stellar winds is derived from the equations for a multispecies plasma with known temperature profiles by assuming that the electron thermal and light speeds approach infinity. Gerald Browning and Tom Holzer have proved the reduced system to be ill posed near the sonic point of the protons for many of the standard parameter cases. Strictly speaking, the unmodified system (from which the reduced system is derived) is well posed for these cases, but there is growth in some of the Fourier modes. They have introduced an alternate system (the "approximate" system), in which the electron thermal and light speeds are slowed down. The approximate system retains the mathematical behavior of the unmodified system and can be shown to accurately describe the smooth solutions of the unmodified system. The approximate system has a number of other advantages over the reduced system. For example, when the proton speed approaches the electron sound speed, the reduced system becomes inaccurate. Also, for three-dimensional flows, the correct reduced system requires the solution of an elliptic equation, while the approximate system is hyperbolic and only requires a time step approximately one order of magnitude less than the reduced system. They compare numerical solutions from models based on the two systems with each other to illustrate these points.

Paul Swarztrauber has developed an $O(\log^2 N)$ parallel algorithm for computing the eigenvalues of a symmetric tridiagonal matrix using a parallel algorithm for computing the zeros of the characteristic polynomial. The method is based on a quadratic recurrence in which the characteristic polynomial is constructed on a binary tree from polynomials whose degree doubles at each level. Intervals that contain exactly one zero are determined by the zeros of polynomials at the previous level, which ensures that different processors compute different zeros. The exact behavior of the polynomials at the interval endpoints is used to eliminate the usual problems induced by finite precision arithmetic.

Swarztrauber and Charles Tong (Sandia National Laboratories-Livermore) have examined design alternatives for ordered FFT algorithms on massively parallel hypercube multiprocessors such as the Connection Machine. Particular emphasis is placed on reducing communication that is known to dominate the overall computing time. To this end, the order and computational phases of the FFT are combined and sequence-to-processor maps that reduce communication are used. The class of ordered transforms is expanded to include any FFT in which the order of the transform is the same as that of the input sequence. Two such orderings are examined, namely, "standard-order" and "A-order," which can be implemented with equal ease on the Connection Machine where orderings are determined by geometries and priorities. A performance of 0.9 Gflops was obtained for an A-order transform on the Connection Machine.

Swarztrauber and David Bailey (NASA Ames Research Center) have developed an efficient method for the detection of a continuous-wave (CW) signal with a frequency drift that is linear in time. Signals of this type occur if the transmitter and receiver are accelerating relative to one another, for example, transmissions from the Voyager spacecraft. They have developed an efficient algorithm for detection using a variant of the FFT called the fast fractional Fourier transform. It admits computation by an algorithm that has complexity proportional to the fast Fourier transform. Whereas the discrete Fourier transform (DFT) is based on integral roots of unity e^{-}, the fractional Fourier transform is based on fractional roots of unity $e^{-\alpha}\frac{2\pi i}{n}$, where α is arbitrary. The fractional Fourier transform and the corresponding fast algorithm are useful for such applications as computing DFTs of sequences with prime lengths, computing DFTs of sparse sequences, analyzing sequences with noninteger periodicities, performing high-resolution trigonometric interpolation, and detecting signals with linearly drifting frequencies. In many cases, the resulting algorithms are faster by arbitrarily large factors than conventional techniques.

DAAC Proposal

A proposal was prepared and submitted to NASA for NCAR to become an Earth Observing System Data Information Systems (EOSDIS) Distributed Active Archive Center (DAAC) site. DAAC sites are centers for EOS data product generation and archiving for satellite data originating from EOS. Since the proposal was submitted, NASA has generated a new designation for DAAC sites such as NCAR, where there is a large science contingent, but where EOS data would not directly flow. If the proposal is accepted, NCAR would become an Affiliated Data Center (ADC).

The CSS has participated in the EOSDIS data panel activities and the system design reviews for the Earth Observing System data gathering and management effort. During late FY 90 and perhaps in early FY 91, the section will participate in the final reviews of the EOSDIS procurement document. It will also participate in other activity relating to the EOSDIS data panel.

The CSS worked with TRW and IBM to develop EOSDIS prototyping activities at NCAR. The concept was to establish procedures at NCAR in which SCD would become a prototype DAAC with a network connection to a simulated information management center located elsewhere. It was felt that a window of opportunity for prototyping existed prior to the release of the EOSDIS Request for Proposal (RFP) by NASA.

Two activities were begun. One was to perform a retrieval of TOVS data using a program ported from the CYBER 205 at NASA Goddard Space Flight Center to the COS machine at NCAR. Subsequently, a year's data was to be retrieved using the program elsewhere. At some point, it was expected that an experiment with a four-dimensional retrieval using the NCAR CCM would be conducted at NCAR. The second activity involved rearranging the World Ocean Circulation Experiment (WOCE) data set in a more efficient manner so that the number of cartridges to be searched to retrieve a time series of the data would be reduced.

By mid-FY 90, this prototyping activity slowed. It was evident that the required assimilation algorithms were not readily available, and it became necessary to reevaluate the potential of the prototyping because of conflict of interest and corporate priorities. Further, the generation of the display software for the WOCE rearrangement took longer than originally anticipated. In FY 91, these activities may continue if no conflict arises with either the need to respond to the EOSDIS RFP or with NCAR's proposal to become a site involved in EOS support, and the window of opportunity still exists.

The CSS staff prepared a joint proposal to NASA with Bill Emery (University of Colorado at Boulder) and Jeff Dozier (University of California Santa Barbara) for a mini-EOSDIS satellite data archiving and presentation service. If the proposal is accepted, an effort will be made to find science investigators interested in the data that is being collected.

NOAA Study

The CSS staff submitted a proposal to NOAA to study their current network and to make recommendations for future improvements. The proposal was accepted and the study completed. Under the proposal, the following subjects were addressed: the study of NOAA's Tier-1 Climate and Global Change (CGC) projects that quantified the networking needs of their CGC effort; comparison of the U.S. data centers; and estimates of the transmission needs for these centers.

Joint Use Projects

NCAR Lead User	Collaborating Institution
Bailey, Paul	University of Colorado
Baumhefner, David	University of Colorado
	University of Utah
Boville, Byron	University of Washington
Branstator, Grant	University of Colorado
	University of Utah
Brown, Tim	University of Colorado
Browning, Gerald	California Institute of Technology
Caldwell, Ginger	Special
Chatfield, Bob	University of Oslo
Chervin, Robert	Various Universities
Clark, Terry	University of Arizona
	Bureau of Reclamation
	Johannes Gutenberg University
	University of Wisconsin, Milwaukee
Coakley, James	Sea Space
Daniels, Mike	Various Universities
Friesen, Dick	Various Universities
Garcia, Rolando	University of Colorado
Gille, John	University of Colorado
	Drexel University
	University of Washington
Gilliland, Ron	University of Arizona
Hack, James	Naval Postgraduate School
	Various Universities
Hedstrom, Kate	Institute for Naval Oceanography
Herring, Jackson	Massachusetts Institute of Technology
Herzegh, Paul	Various Universities
Heymsfield, Andrew	University of Chicago
Isradar, Barnes	Various Universities
Jenne, Roy	Colorado State University
	University of Utah
	University of Washington
	Various Universities
Joseph, Dennis	University of Washington
	Various Universities
Kasahara, Akira	University of Utah
Kiehl, J.	University of Chicago
	State University of New York, Albany
Kuo, Ying-Hwa	Pennsylvania State University
	University of Washington
Lamb, George	University of Alaska
Lites, Bruce	University of Colorado
Madden, Roland	Colorado State University
Mankin, William	Denver University
	Various Universities
Miller, Jay	NOAA
	Various Universities
Nordlund, Aake	Various Universities
Oye, Richard	Various Universities
Parsons, David	Colorado State University
Pouquet, Annick	Observatoire de Nice
Rasch, Philip	University of Chicago
Rasmussen, Roy	Various Universities
Richmond, Art	University of California, Los Angeles
	University of Colorado
Roble, Ray	University of Alaska
	Univerity of Arizona
	University of Colorado
	Various Universities
Rotunno, Richard	Massachusetts Institute of Technology
	Purdue University
Shea, Dennis	Institute of Meteorology
Smolarkiewicz, Piotr	University of Miami
Stordal, Frode	University of Oslo
Swarztrauber, Paul	Stanford University
Trenberth, Kevin	University of Alabama
	University of Illinois
Tribbia, Joseph	Yale University
Van Loon, Harry	University of Colorado
	Iowa State University
Vaughan, Robin	Various Universities
Wade, Charles	Various Universities
Warner, Jack	Desert Reseach Institute
Washington, Warren	Colorado State University
	University of Michigan
	University of Wisconsin
Wyngaard, John	Battelle Laboratories
Zipser, Edward	Colorado State University

University Users

Principal Investigator and Number of Users by University

University of Alabama

Comfort, Richard	2
Knupp, Kevin	1

University of Alaska

Rees, M.	2
Tanaka, Hiroshi	2

University of Arizona

Gall, Robert	3
Hunten, Donald	1
Zhender, Joseph	3

Applied Research Corporation Technology

Crowley, Thomas	5

Atmospheric & Environmental Research, Inc.

Rosen, Richard	3
Wang, Wei-Chyung	6

University of British Columbia

Pielke, Roger	4

California Institute of Technology

Liu, W.	4
McKoy, Vincent	2

University of California, Davis

Grotjahn, Richard	5
Nathan, Terrence	3

University of California, Irvine

Friehe, Carl	1

University of California, Los Angeles

Arakawa, Akio	11
Blier, Warren	1
Dawson, John	4
Knipp, Major Delores	1
Kreiss, Heinz	2
Mechoso, Carlos	3
Neelin, J. David	3
Wakimoto, Roger	3
Yanai, Michio	3

University of California, San Diego

McClymont, Alexander	3

Center for Environment and Man

Saltzman, Barry	4

University of Chicago

Bannon, Peter	6
Braham, Roscoe	4
Donner, Leo	1
Fujita, T.	5
Konigl, Arieh	1
MacAyeal, Douglas	3
Ramanathan, V.	5
Srivastava, Ramesh	4
Ziegler, Alfred	1

Clarkson College

Fulton, Scott	2

Colorado School of Mines

Bell, Jean	1

Colorado State University

Bringi, V.	7
Cotton, William	38
Gray, William	3
Hjelmfelt, Mark	2
Johnson, Richard	4
McKee, Thomas	1
Pielke, Roger	51
Randall, David	16
Rogers, David	6
Rutledge, Steven	5
Schubert, Wayne	11
Stephens, Graeme	8
Stevens, Duane	12
Vonderhaar, Thomas	1

University of Colorado

Avery, Susan	2
Bannon, Peter	1
Barry, Roger	2
Begelman, Mitchell	3
Blumen, William	3
Cathey, W. Thomas	2
Dunn, Gordon	2
Dusenbery, Paul	3
Emery, William	2
Fesen, Cassandra	2
Gillette, Dale	1
Goldman, Martin	6
Grossman, Robert	3
Hanson, Howard	3
Hart, J.	1
Haupt, Sue Ellen	1
Hay, William	5
Hummer, David	6
Hynes, James	2
Kiladis, George	3
Kraus, Eric	5
London, Julius	4
McCormick, Stephen	2
Rosner, Robert	2
Salby, Murry	3
Smith, Dean	2
Solomon, Stanley	1
Sweet, Roland	1
Wahr, John	2

Walker, Donald	2
Columbia University	
Cane, Mark	2
Garzoli, Silvia	2
Miller, Robert	4
Control Data	
O'Sullivan, Donald	1
Cornell University	
Shapiro, Stuart	3
University of Delaware	
Church, Thomas	2
University of Denver	
Goldman, Aaron	15
Murcray, David	19
Patel, Vithalbhai	3
Drexel University	
Kay, Jack	3
Riordan, Allen	1
Florida State University	
Ahlquist, Jon	3
Krishnamurti, T.	10
Pfeffer, Richard	7
Ray, Peter	4
Smith, Eric	2
Surgi, Naomi	2
Harvard University	
Farrell, Brian	3
Jacob, Daniel	2
Marcus, Philip	4
McElroy, Michael	3
Smyth, William	2
University of Hawaii, Honolulu	
Chen, Yi-Leng	4
Firing, Eric	1
Hua, Bach Lien	1
University of Illinois, Ubana	
Mak, Mankin	2
Ogura, Yoshimitsu	4
Schlesinger, Michael	3
Walsh, John	3
Institute for Scientific Research	
Guberman, Steven	1
Iowa State University	
Chen, Tsing-Chang	10
Stanford, John	2
Takle, Eugene	4
University of Iowa	
Goertz, Christopher	2
Nicholson, Dwight	6
Hyushu University	
Takahashi, Tsutomu	1
Johns Hopkins University	
Evan, James	5
Haidvogel, Dale	4
University of Kansas	
Pielke, Roger	3
University of Lowell	
Crowley, Geoffrey	2
University of Maryland	
Baer, Ferdinand	5
Carton, James	6
Chao, Shenn-Yu	3
Dickerson, Russell	2
Schneider, Edwin	3
Shukla, J.	17
Straus, David	2
Massachusetts Institute of Technology	
Bras, Rafael	3
Dole, Randall	7
Emanuel, Kerry	3
Lindzen, Richard	1
Marcus, Philip	1
Meacham, Stephen	2
Pedlosky, Joseph	2
Plumb, R.	1
Rizzoli, Paola	7
Wunsch, Carl	3
Young, William	5
University of Miami	
Bleck, Rainer	14
Lee, Thomas	2
Pitcher, Eric	5
Prospero, Joseph	3
Michigan Technological University	
Ierley, G.	1
University of Michigan	
Cravens, Thomas	6
Gombosi, Tamas	7
Killeen, Timothy	4
Mullen, Steven	6
Nagy, Andrew	7
Smith, Anne	3
Torr, Douglas	2
Middlebury College	
Winkler, P. Frank	1
University of Missouri, Rolla	
Hale, Barbara	2
Salk, Sung	3
Naval Postgraduate School	
Batteen, Mary	5
Chang, Chih-Pei	4
Nuss, Wendell	1

Semtner, Albert , Jr.	10
University of Nebraska	
Verma, Shashi	3
New Mexico Institute of Mining and Technology	
Raymond, David	3
Winn, William	4
University of New Mexico	
Gosz, James	3
State University of New York, Albany	
Middleton, Paulette	7
Molinari, John	2
No Affiliation	
Kraichnan, Robert	1
NOAA	
Watterson, Ian	1
North Carolina State University	
Burniston, E.	1
Raman, Sethu	4
Northwest Research Associates, Inc.	
Dunkerton, Timothy	3
Northwestern University	
Birchfield, G. Edward	2
Nova University	
Snyder, Russell	4
University of Oklahoma	
Bluestein, Howard	6
Carr, Frederick	6
Droegemeier, Kelvin	15
Gal-Chen, Tzvi	1
Lilly, Douglas	9
Wilkins, Eugene	2
Xu, Qin	3
Old Dominion University	
Cutter, Gregory	1
Klinck, John	2
Oey, Lie-Yauw	2
Oregon State University	
Allen, John	3
Barth, John	1
Coakley, James	7
Esbensen, Steven	6
Mahrt, Larry	7
Miller, Robert	2
Rutledge, Steven	4
Schlesinger, Michael	11
Strub, Paul Ted	1
Pennsylvania State University	
Albrecht, Bruce	5
Aydin, Kultegin	3
Bannon, Peter	1
Barron, Eric	13
Clark, John H.	1
Forbes, Gregory	21
Frank, William	6
Fritsch, Michael	6
Kasting, James	6
Kump, Lee	10
Seaman, Nelson	3
Shirer, Hampton	5
Warner, Thomas	24
Webster, Peter	8
Portland State University	
O'Brien, Robert	3
Princeton University	
Orszag, Stephen	5
Seidl, Frederick	1
Purdue University	
Agee, Ernest	4
Harshvardhan	4
Snow, John	4
University of Rhode Island	
Arimoto, Richard	3)
Arthur, Michael	2
Duce, Robert	1
Huebert, Barry	4
Leinen, Margaret	3
Merrill, John	5
Rice University	
Lane, N.	2
Ledley, Tamara	4
Rutgers University	
Avissar, Roni	3
Sacramento Peak National Observatory	
Teem, John	1
Scripps Institution of Oceanography	
Barnett, Tim	2
Graham, Nicholas	1
Roads, John	1
University of South Carolina	
Eian, James	5
South Dakota School of Mines and Technology	
Farley, Richard	5
Helsdon, John	4
Orville, Harold	7
Sengupta, Sailes	4
Smith, Paul , Jr.	6
St. Louis University	
Rao, Gandikota	1
Stanford University	
Inan, Umran	4
Street, Robert	1

Tel Aviv University

Starr, David	3

Texas A & M University

Das, Phanindramohan	2
Hofmann, Eileen	2
Panetta, R. Lee	2

Texas Tech University

Chang, Chia-Bo	1

University of Texas, Austin

Tajima, Toshi	5

University of Texas, Dallas

Heelis, R.	1

Towner-Hastings Associates

Hastings, Jordan	2

Trinity College

Brown, Philip	2

Trinity University

Dickey, John	3

Utah State University

Schunk, Robert	6

University of Utah

Durran, Dale	4
Horel, John	6
Liou, Kuo-Nan	9
Nogues-Paegle, Julia	12
Paegle, Jan	1
Sassen, Kenneth	1

University of Virginia

Galloway, James	4

University of Washington

Baker, Marcia	1
Hartmann, Dennis	4
Hobbs, Peter	0
Holton, James	8
Houze, Robert	2
Kawase, Mitsuhiro	5
Leovy, Conway	1
Mass, Clifford	5
Reed, Richard	2
Rhines, Peter	4
Riser, Stephen	3
Teem, John	1
Wallace, John	5
Warren, Stephen	14

University of Wisconsin, Madison

Anderson, Charles	1
Battisti, David	4
Hitchman, Matthew	7
Houghton, David	14
Johnson, Donald	15
Kutzbach, John	13
Raymond, William	1
Schlesinger, Robert	1
Tripoli, Gregory	5
Unknown	1
Young, John	1

University of Wisconsin, Milwaukee

Unknown	1

Woods Hole Oceanographic Institution

Beardsley, Robert	2
Chapman, David	5
Geyer, W. Rockwell	1
Huang, Rui Xin	2
Pedlosky, Joseph	1
Royer, Thomas	1
Samelson, Roger	1

University of Wyoming

Parish, Thomas	1
Rodi, Alfred	3

Yale University

Park, Jeffrey	2
Saltzman, Barry	4
Smith, Ronald	2
Turekian, Karl	1

Staff

Administrative Section

Bill Buzbee (director)
Julia Chapin
Rachelle Daily
Sylvia Darmour
Karen Friedman
Belinda Housewright
JoAn Knudson
Louise Lawrence
Rosemary Mitchell
Percy Peterson (manager)
Janice Powell
Betty Thompson (administrator)
Janie Young

Computational Support Section

Jeanne Adams
John Adams
Gerald Browning (manager)
Paul Rotar
Richard Sato
Paul Swarztrauber
Roland Sweet

Computer Operations and Maintenance Section

Donna Barday-Rowland
Gregory Berman
Melissa Breedlove
Glenn Brown
Mary Buck
Douglas Chaney
Steven Chapel
Gaynez Connell
Randy Eastin
Marlene Furmanek
Delbert Harris
Ed Heitschel
Gary Jensen (manager)
Sue Ellen Jensen
Richard Lindenmoyer
Stan McLaughlin
Susan McLaughlin
Long Moua
Robert Niffenegger
Scott Quinn
Andrew Robertson
James Robinson
Roxanne Romero
David Rowland
Suzanne Scarborough
Susan Schemel
Larry Scott
Valerie Shanahan
David Strayer
Nancy Waldron
Wesley Wildcat

Data Support Section

Roy Barnes (20%)
Roy Jenne (manager)
Dennis Joseph
Wilbur Spangler
Gregg Walters
Steven Worley

Distributed Computing Section

Daniel Anderson
Britt Bassett
Jeff Boote
Joseph Choy (manager)
Frederick Clare
John Clyne
Esther Herold
David Kennison
Robert Lackman
Marla Meehl
Don Middleton-Link
Donald Morris
Herbert Poppe
James Weber
Christopher Webster
Greg Woods

Systems Section

Edward Arnold
Barbara Bateman
Phylecia Brandley
Dennis Colarelli
Kathryn Fryberger
George Fuentes
Gilbert Green
Eugene Harano
Darrell Holley
Basil Irwin
David Kitts
John Merrill
Bernard O'Lear (manager)
Craig Ruff
Eugene Schumacher
John Sloan
Erich Thanhardt
Mark Uris
Sandra Walker

User Services Section

Brian Bevirt
Ginger Caldwell (manager)
Susan Cross
Nancy Dawson
Christine Guzy
Sally Haerer
Kenneth Hansen
Jeff Kuehn
Lynda Lester
Jacque Marshall
Adrianne Middleton-Link
Peter Morreale
Thomas Parker
Juliana Rew
Susan Smith
Richard Valent

Publications

Refereed Publications

ADAMS, J. C., 1989: FMG Results with the Multigrid Software Package MUDPACK. In *Proc. of the Fourth Copper Mountain Conference on Multigrid*, Copper Mountain, CO, Society for Industrial and Applied Mathematics, 1–12.

——, 1989: MUDPACK: Multigrid Fortran Software for the Efficient Solution of Linear Elliptic Partial Differential Equations. *Applied Mathematics and Computation*, 34, 113–146.

BRAINERD, W. S., C. H. GOLDBERG, and J. C. ADAMS, 1990: *Programmer's Guide to FORTRAN 90*, McGraw-Hill Book Co., 406 pp.

Other Publications

BROWNING, G.L., W.R. HOLLAND, H.-O. KREISS* and S.J. WORLEY, 1990: An Accurate Hyperbolic System for Approximately Hydrostatic and Incompressible Oceanographic Flows. *Dynamics of Atmospheres and Oceans*, 14, 303–332.

BUZBEE, B., 1990: Supercomputing and the Environment, *Supercomputer 36*, ASFRA, The Netherlands, 7 (2), 7–17.

CLARE, F.J., and D.J. KENNISON, N.A. Dawson (Project Leader), *NCAR Graphics Guide to New Utilities*, Version 3.00: 1990, NCAR Technical Note NCAR/TN-341+STR, NCAR, Boulder, CO, 423 pp.

FRIEDMAN, K. D. and B.T. O'LEAR, Eds., 1990: *Digest of Papers*, Proc. Tenth IEEE Symposium on Mass Storage Systems, IEEE Computer Society Press, 187 pp.

FRIEDMAN, K. D., Ed., 1989: *Supercomputing: The View from NCAR, FY89 Review and FY90-91 Development Plan for the NCAR Scientific Computing Division*, NCAR, 139 pp.

*GEORGE, R., and R. LACKMAN, 1990: *Survey of NCAR User Needs for Visualization Tools*, NCAR Technical Note NCAR TN +354+STR, NCAR, Boulder, CO, 49 pp.

MERRILL, J., and E. THANHARDT, 1990: Early Experience with Mass Storage on a UNIX-Based Supercomputer, *Digest of Papers*, Proc. Tenth IEEE Symposium on Mass Storage Systems, IEEE Computer Society Press, 117–121.

SWARZTRAUBER, P. N., and R. K. SATO, 1990: Solving the Shallow Water Equations on the CRAY X-MP/48 and the Connection Machine 2, In *The Dawn of Massively Parallel Processing in Meteorology*, (G.R. Hoffman and D.K. Maretis, Eds.), Series: Topics in Atmospheric and Oceanic Sciences, Springer-Verlag, 260–276.

* An asterisk denotes a non-NCAR author.

Educational Activities

NCAR's educational activities in the atmospheric sciences cover all school levels, from kindergarten through postdoctoral research, and extend to the general public. The Advanced Study Program has provided opportunities for graduate and postdoctoral students almost since the beginning of NCAR, and attention to the early years of learning has blossomed during the past five years, especially through the Education and Tour Program. This growing effort organizes visits from students and teachers, fills information requests, and distributes products and programs that explain NCAR research to young audiences.

The Advanced Study Program (ASP) was created early in the history of NCAR to provide a mechanism for looking to the future of the atmospheric sciences. This function is exercised today in two ways: ASP arranges for a number of scientists at the beginning of their careers to work for a time at NCAR, both to gain familiarity with work on major atmospheric science problems and to learn how to make best use of NCAR's capabilities; and ASP provides for the examination of research areas that are particularly timely or that, despite having long-term importance, are relatively underemphasized at NCAR or in the community. The first of these activities—bringing new scientists to NCAR—is organized within the Visitor Program. The second—supporting selected areas of research—consists of convening workshops on forward-looking issues, selecting visitors from a wide spectrum of interests to work with NCAR staff, and supporting more experienced visitors in areas of possible future importance to the atmospheric sciences.

Significant Accomplishments

- Chris Davis focused on the dynamics of extratropical cyclones, especially the feedback of precipitation processes on their structure, motion, and intensity, using potential vorticity as a diagnostic variable during his postdoctoral appointment with ASP and the Mesoscale and Microscale Meteorology Division (MMM).

- Lee Klinger played a key role at NCAR in initiating carbon cycling research on peatlands, involving both field and laboratory studies, which suggested that northern peatlands are a much smaller source of methane than previously thought. He also formulated and has begun to test a hypothesis that proposes that gradual expansion of peatlands, over thousands of years, may aid in the initiation of ice ages.

- Linda Mearns, with Stephen Schneider, Starley Thompson, and Larry McDaniel (Climate and Global Dynamics Division, or CGD), evaluated the control run output of three different versions of the NCAR community climate model for selected regions of the United States. In addition, for one version the doubled-CO_2 output was examined. In particular, how well the models reproduced the daily variability of temperature and precipitation was evaluated. A significant finding was that with an improved surface package (Biosphere-Atmosphere Transfer Scheme) daily temperature variability was much more accurately reproduced compared to the other versions with very simple surface processes.

- NCAR and the University of Colorado's School of Education developed "Weather Wizards," a series of five classes designed for elementary school children. Part of the after-school Science Discovery Program, the classes introduced students to weather concepts, instruments, and experiments.

- NCAR Information Services, in conjunction with Centre Productions of Boulder, Colorado, produced a 20-minute video for junior high school students called *Weather Dynamics*. The video, illustrated with live experiments, explains clouds, tornados, microbursts, and basic principles of weather. It is being made available nationally.

Advanced Study Program

Each year ASP awards appointments as postdoctoral fellows or as graduate research assistants to a number of new scientists. These appointments fulfill several purposes: to permit young scientists to work with groups at the forefront of the science, to ensure that there will be in the university and government communities scientists who are familiar with NCAR's capabilities, and to add energy and creativity to the NCAR research programs. Increasingly in the past few years, these programs have also been used, experimentally, to enlarge NCAR's contacts with fields of obvious importance to studies of climate and climate change but not traditionally part of atmospheric research. Examples of such fields are ecology (including paleontology, the reconstruction of past climates, and the interaction of the atmosphere with ecosystems) and political science (how peoples cope with climate change or how economic development interacts with climate). New scientists in such areas may not remain formally in the atmospheric sciences at the end of their appointments, but they will be in a much-improved posture to join with those studying climate in the many multidisciplinary projects that will be required in the future.

While in residence at NCAR, each graduate assistant carries out research based on his or her thesis proposal, which must be endorsed jointly by the university thesis adviser and an NCAR scientist. In fiscal year 1990 (FY 90), 17 ASP graduate research assistants were in residence at NCAR: 8 had new appointments, 3 had continued appointments, and 6 completed their terms; of the latter, 3 received Ph.D. degrees during the year.

While at NCAR, students work directly within ongoing research programs. The efforts of 11 of the students are described in this section; other sections of this report describe the work of the other 6.

The High Altitude Observatory (HAO) also awarded graduate assistantships in FY 90. Information on those appointments appears within that division's report.

During FY 90, 7 new ASP postdoctoral fellows began appointments, 16 continued from the previous year, and 9 fellows completed their terms. As with the graduate assistants, much of the work of the fellows is presented in the reports of the research divisions.

Dynamical Theory

The complex motions found in the sun, oceans, and atmosphere are far from being completely described or satisfactorily understood. A number of ASP fellows and students chose to study the physics of particular forms of motions possible in fluid systems on rotating spheres.

The atmosphere and ocean contain many kinds of coherent structures, including waves, jets, and vortices. Because of the rapid rotation of the earth, geophysical flows are often approximately two-dimensional. During the past year, Jeffrey Weiss undertook two separate studies of the role of coherent structures in two-dimensional flows.

One study focused on the influence of waves on the transport and mixing properties of a fluid. Such properties are important in many geophysical problems, including acid precipitation and ozone depletion in the atmosphere, and salinity transport in the oceans. Weiss found that waves can have a profound influence on the transport and mixing properties of a fluid, producing enhanced transport and anomalous diffusion.

The second project was a study of the properties of coherent vortices in two-dimensional decaying turbulence. Weiss obtained excellent agreement among high-resolution simulations of the Navier-Stokes equations, a new model of turbulence in terms of the deterministic chaotic dynamics of point vortices, and a new scaling theory of the vortex properties. This work is being carried out in collaboration with James McWilliams (CGD), George Carnevale, William Young (both at the Scripps Institution of Oceanography), and Yves Pomeau at École Normale Supérieure, Paris, France.

Helioseismic observations of solar acoustic and fundamental modes are providing important information about the internal structure and dynamics of the sun. The fundamental modes are essentially surface gravity waves, similar to the water waves observed on the ocean surface. One perplexing problem is that the measured frequencies of the fundamental modes are smaller than the frequencies predicted by the well-known surface wave dispersion formula $\omega^2 = gk$, where ω and k are, respectively, the frequency and wave number of the mode, and g is the gravity at the solar surface. The discrepancy is greatest at the largest wave numbers.

Eugene Lavely sought to explain this discrepancy by modeling effects generally ignored for fundamental modes. It is generally assumed that the modes are (1) compressionless, (2) insensitive to density stratification, and (3) not affected by gravitational potential perturbations that their motions induce. The formula $\omega^2 = gk$ is appropriate for a plane-parallel atmosphere. Lavely derived the corresponding result in spherical geometry using assumption (1) only. Preliminary results indicate better agreement with the data. More importantly, the new result may be used to constrain the thermal stratification of the thin superadiabatic layer near the surface of the sun. For a variety of reasons, this region is normally inaccessible to analysis. Constraints on this region could be used to test the validity of mixing-length theories.

Coherent structures are an important part of geophysical flow, but they are not well understood. Examples of such long-lived features include atmospheric blocking, Gulf Stream rings, and the Great Red Spot of Jupiter. The longevity of these structures is best explained by nonlinear dynamics. Modons, exact two-branched dipole solutions of the quasi-geostrophic vorticity equations, have been used to represent coherent structures. However, the real geophysical structures are more complex since they are embedded within a shear flow.

Sue Ellen Haupt investigated modons within shear flows by computing equilibrium solutions of the equivalent barotropic vorticity equation. The spectral model, which uses a Newton-Kantorovich iterative technique, is given a first guess of an exact prototype modon with a small shear flow imposed, then iterated to an equilibrium solution. Continuation is used to produce examples of modons embedded in moderate amplitude background shear flows. Haupt found that in the presence of symmetric shear, the modon is strengthened relative to the prototype. The best-fit phase speed for this case is significantly greater than the Doppler-shifted speed. Nonsymmetric shear strengthens the poles selectively: positive shear strengthens the low while weakening the high. The modons in symmetric shear appear to be stable within time integrations, at least for small to moderate shear amplitudes. The stability of modons in antisymmetric shear is less certain. Although they are likely to be unstable for moderate-amplitude shear, they remain coherent enough to represent geophysically relevant structures.

This study strengthens the plausibility of using modons as a model of coherent structures in geophysical flow.

A primary characteristic of turbulent flows is random distribution of three-dimensional vortices. Hence, it is of interest to understand the fundamental interactions of vortices in order to understand and model turbulent flows. An interesting topology-nonpreserving vortex interaction of two opposite signed vortices, called vortex reconnection, has been observed in flow visualization of interacting vortex rings and various jet flows, specifically in elliptic jets of high aspect ratios and in the breakdown of circular vortices at the end of jet column mode. As his thesis topic at the University of Houston, Davinder Virk undertook to study the effects of compressibility on vortex reconnection.

In order to study this interaction, Virk produced direct numerical simulations using idealized initial conditions from earlier studies. Virk modified the code Robert Kerr (MMM) had written to solve incompressible Navier-Stokes equations, in order to simulate compressible Navier-Stokes equations. The new code solves evolution equations for density and pressure in addition to those for velocity. This code also has the provision to consider viscosity and conductivity as functions of temperature. The spatial discretization is done using a Fourier spectral method, and time stepping is done by a third-order Runge-Kutta compact storage version of Allen Wray's (NASA, Ames, Iowa).

Virk considered two different models of compressible vortex. The first model has constant density in the initial conditions, and the second model uses a polytropic relation between the density and pressure; the pressure in both the models is calculated so as to make the rate of change of divergence zero. He found that if the pointwise maximum Mach number (M) in the initial condition did not exceed 0.5, then both models gave results which were consistent with the incompressible results. However, for pointwise maximum M greater than 1.0, the two models showed drastically different results. The model with constant initial density showed results similar to the low M case; however, the model with variable initial density led to results strongly affected by compressibility. These results demonstrate that the compressible simulations are strongly influenced by the initial conditions. Because in vortex reconnection simulations the flow is almost incompressible except near the interacting vortices, Virk speculated that even for a largely incompressible high-Reynolds-number flow, the compressible effects can be important at small scales, if the flow near the interacting vortices becomes locally supersonic.

The question of how a stratified fluid adjusts to equilibrium under the effects of gravity remains a central problem of geophysical fluid dynamics since it is fundamental to understanding how the ocean and the atmosphere behave. When no external forcing is present, an initially unstable flow will adjust to a steady-state equilibrium by radiating away some energy in the form of waves. When the horizontal scale of the flow is much smaller than the Rossby radius of deformation, the equilibrium is between the centrifugal force and the pressure gradient.

Pascale Lelong and McWilliams continued their investigation of the adjustment of a variety of initial flow configurations in the shallow-water approximation using a combination of analytic and numerical methods. For flows that were a function of a single spatial variable, such as axisymmetric flows, solutions for the final state were obtained by invoking conservation laws for mass, angular momentum, and potential vorticity.

The adjustment of more complicated initial configurations was simulated with a shallow-water code written by Nancy Norton (CGD). In addition to varying the shape of the initial structure, Lelong and McWilliams investigated the Froude number dependence of the solutions. As the Froude number increased, nonlinear effects became more pronounced, and the amount of energy lost in the form of radiated gravity waves during the adjustment process increased. Regimes in parameter space in which adjustment is never possible were also identified.

Models

Numerical models form the backbone of much of NCAR's work.

Jeffrey Proehl continued his studies of the parameteric dependence of tropical instability waves in the three-dimensional numerical model of the upper tropical ocean. His preliminary results show the waves to be sensitive to the vertical structure of the vertical mixing parameters and relatively insensitive to its magnitude.

In collaboration with Jane Cullum (Thomas J. Watson Research Center of IBM, Yorktown Heights, New York), Proehl developed an eigenvalue solver. This solver, whose development was essential to address the problems of interest, was successfully tested on the NCAR Cray Y-MP8/864. In developing this tool, Proehl not only devoted considerable effort to determining the most compact and efficient formulation of the eigenvalue problem, but he also conducted a study of the dispersion characteristics of the equatorial wave modes in numerical models. This new tool will be used in the direct investigation of the stability of equatorial zonal mean flows and will be applied to idealized mean flows, observed flows, and mean flows obtained from the three-dimensional time-stepping model. Its use will, therefore, be both independent of and complementary to the analysis of the tropical instability waves from the three-dimensional time-stepping model.

Eugene McCaul found in earlier work that landfalling hurricanes are characterized by conditions favorable for the development of rotating, potentially tornadic, convective storms. Numerical simulations indicated that the storms were likely to be somewhat smaller than tornadic storms from the Great Plains. This was in agreement with the limited number of data in published observational studies. The hurricane-spawned storms achieved their intensity primarily through the action of perturbation pressure forces, which were particularly strong because of the vertical stratification of buoyancy and shear in the environment. In 1990, McCaul began a series of numerical simulations aimed at uncovering how convective storm intensity and morphology respond to the vertical structure of the ambient buoyancy and shear. In these simulations, a convective cloud model is initialized with thermal bubbles in environments having constant amounts of vertically integrated buoyancy and shear, but with sharply differing vertical distributions of those quantities. Preliminary indications are that significant differences exist between the intensities of the storms simulated under these various conditions. In particular, the strongest storms tend to occur when buoyancy and shear are concentrated together in the lowest layers of the storm environment.

Potential vorticity (PV), defined by Rossby and Ertel, is the fundamental dynamical quantity governing midlatitude cyclone development. Long-standing questions regarding the influence of latent heat release, surface energy fluxes, and turbulent mixing may be addressed in terms of how each changes the cyclone-scale distribution of PV. Chris Davis, in cooperation with Kerry Emanuel (Massachusetts Institute of Technology), used a mathematical relationship of PV to the balanced flow to assess the importance of observed PV perturbations in cyclone development. Three recurring structures were identified in each of several cyclogenesis cases: Rossby waves propagating along the tropopause and along the surface baroclinic zone and interior PV anomalies generated by latent heat release in the ascent region of the cyclone.

Because PV created by condensation is free to interact with other PV perturbations, the overall effect of moisture cannot be assessed by the instantaneous rate of PV generation. Davis and Ying-Hwa Kuo (MMM) have undertaken a study using the MM4 mesoscale model (developed jointly by Pennsylvania State University and NCAR) to determine the total interaction of the diabatically created PV with the rest of the fluid. Their approach is to diagnose PV in simulations of observed cyclones with and without latent heat release. For a case of explosive cyclogenesis over the central United States, Davis and Kuo found that low-level PV (below 600 mb) generated by condensation accounted for about one-third of the mature cyclone's low-level circulation in the moist simulation. Furthermore, the flow from this PV anomaly increased the eastward speed of the surface front by several m/s relative to the dry simulation. This was crucial for the timing and location of subsequent secondary cyclogenesis along the East Coast.

Several recent studies have been concerned with the existence of multiple stable equlibria for the oceanic thermohaline circulation. This circulation plays an important role in the climatic variations. It is driven by density forcing due to the temperature and salinity surface distributions, and responds on time scales on the order of millennia. Continuing the modeling effort reported last year, Olivier Thual and McWilliams described the catastrophe structure of a two-dimensional model of the oceanic thermohaline convection. They have shown that this catastrophe structure could be reproduced in simple box models connecting stirred reservoirs through capillary pipes. This analysis provides a framework for a better understanding of climatic transitions between different stable regimes of the ocean-atmosphere system.

It is well known that the errors originating from initial data uncertainties grow in numerical forecasts. Global numerical models treat explicitly only processes with characteristic horizontal scales longer than several hundred kilometers. Consequently, the error growth occurring in these models is associated with synoptic-scale dynamics. Tomislava Vukicevic, in a study based on the mesoscale model integrations, was able to show that even for high-resolution limited-area model forecasts the initial error growth is confined to the synoptic scales. This result suggests that the initial error growth in numerical forecasts is associated with barotropic and baroclinic instabilities in synoptic-scale flow. These instabilities are typically studied using a linear dynamics framework, suggesting that the same framework can be used for studying the evolution of the initial forecast error. In order to investigate this possibility Vukicevic developed the linear version of a sophisticated limited area forecast model. The nonlinear model is the MM4 model. The linearization was performed with respect to a temporally and spatially varying basic state produced by the complete nonlinear model real-data forecast.

The short-time tangent linear model solutions and the error fields based on the nonlinear integrations were compared. These fields are virtually identical in shape and slightly different in amplitudes. These results demonstrate that the major portion of the initial forecast errors can be described by the tangent model solutions for the complete mesoscale forecast model for periods of 1–1.5 days. The results also suggest that the linear model solutions based on time-independent basic states are also good approximations of the initial error evolutions provided that the forecast fields are not changing rapidly in time.

Assimilation of data in numerical models in oceanography or meteorology can be considered a way of blending information from observations and model physics in order to get a more complete and accurate description of the physical world. Data assimilation procedures have been extensively used in meteorology for years as initialization procedures before forecasting. Periodic reinitializations of the model are done in order to account for the finite model predictability time. However, data assimilation in oceanic numerical models is a new and challenging field. In fact, oceanographers have always had to face the paucity of data in terms of both spatial distribution and time duration of measurements, so that any effective assimilation of data was impossible. The recent satellite missions (and other missions planned for the near future) make available data sets with a large coverage over synoptic time scales, making data assimilation in oceanic models a timely and promising project. However, the availability of data only at the surface of the ocean, and also, in some cases, the discrepancy between modeled and observed climatologies require investigation.

Antonietta Capotondi, in collaboration with William Holland (CGD), studied the possibility of assimilating altimeter data (sea surface height) from the GEOSAT mission in a numerical model of the Gulf Stream region. The model is quasi-geostrophic, has five layers and 1/8 degree horizontal resolution, and includes realistic coastline and bottom topography. Due to the complex dynamics of this region, numerical models, including the one in use, fail to reproduce the observed climatology. Therefore data assimilation can also be considered as a tool for correcting the model climatology, and, through the analysis of the assimilation results, a way of understanding the model dynamics. Capotondi is currently performing a spectral analysis of the model fields in order to obtain a statistical description of the model variability. The next step will be an analogous analysis of the data to be assimilated and comparision with the model. Then assimilation will be performed, and the results analyzed in order to understand the internal dynamics of different scales of motion and the most relevant eddy–mean flow interaction processes.

Cumulus parameterization is a very important component in general circulation models (GCMs) and in large-scale numerical weather forecasting models. Most of the existing cumulus parameterization schemes do not include the effect of convective downdrafts, which contribute significantly to the total cumulus mass flux and vertical heat and moisture transports in the lower troposphere. Ming-Dean Cheng constructed a downdraft model that satisfies the conservation of mass, moist static energy, water vapor, total water, and vertical momentum, and includes the evaporation of rainwater and lateral mass exchange between downdrafts and the environment. Cheng is currently working on improving the physical comprehensibility and computational efficiency of the downdraft model. Later, he will focus on the impacts of the parameterized convective downdrafts on the performance of GCMs.

On time scales of up to 1000 years, the ocean controls the amount of CO_2 in the atmosphere. Changes in climate are bound to affect ocean circulation, biology, and chemistry, which in turn may drive CO_2 changes in the atmosphere. Also, the ocean may be the primary sink of anthropogenic CO_2. While at NCAR, Raymond Najjar has begun to formulate a model of the oceanic carbon cycle to address such issues. This model will likely include global oceanic circulation, a several-component ecosystem, and carbon chemistry.

Simulations of long-term future trends of the ozone layer have usually been performed using one-dimensional atmospheric models. These models are useful to describe global-scale changes, but are inadequate to reproduce the influence of local events that could be of great consequence on the global scale, such as the observed spring Antarctic ozone decrease. This event can only be taken into account in two- or, better, three-dimensional models. So far, some two-dimensional models include a parameterized description of the particular polar stratospheric chemistry and have successfully reproduced the ozone hole. In order to forecast the future evolution of the ozone layer, however, a proper description of heterogeneous processes occurring on the surface of aerosol and cloud particles is needed. This in turn requires a background microphysical model of formation and vanishing of such particles.

Anne DeRudder, in collaboration with Guy Brasseur (ACD), is attempting to simulate past as well as future perturbations of the ozone layer and of the atmospheric temperature by variations in the solar activity and by emission of trace gases of industrial or agricultural origin. These studies were performed with the one- and two-dimensional stratospheric models developed at NCAR. The two-dimensional model includes a parameterized polar heterogeneous chemistry. DeRudder is currently working on the theoretical problem of modeling the microphysical behavior of polar stratospheric ice clouds. The next step of the work is to couple the scheme being built to a code of heterogeneous chemistry related to ice particles, with the eventual purpose of including the resulting coupling to the existing two- and three-dimensional stratospheric models.

Peter Hess completed his work on the breakup of mixing of the polar vortex following the final stratospheric warming. The eventual fate of the air once contained within the vortex and the manner and time scale on which this air is mixed following the final warming are important components of the ozone hole problem; the mixing time determines how rapidly the ozone-poor air is diluted or can chemically react with the atmosphere at large. Hess showed that this mixing time is on the order of several months, using both satellite observations and an offline tracer advection model (using winds from the NCAR community climate model).

Hess also studied the Intertropical Convergence Zone (ITCZ), a persistent belt of cloudiness located in the deep tropics with far-reaching implications on the global weather. This study used the NCAR community climate model to stimulate a hypothetical ocean-covered planet, which in every other respect is like the earth. Two portions of this study were essentially completed. In the first, Hess investigated the sensitivity of the modeled climate and of the location of the ITCZ to the parameterized subgrid-scale convection. The second study investigated the sensitivity of the tropical wave spectrum to sea surface temperature.

Northeast of Taiwan, the Kuroshio Current enters the East China Sea, a shallow coastal ocean, and impinges directly on the shelf break. The impingement initiates in that region a massive exchange between the Kuroshio and the surrounding coastal waters. The exchange leads to the formation of a mixed water mass that is a persistent feature of the shelf-break environment between Taiwan and the southern Japanese islands. The objectives of the dissertation research being conducted by John Schultz, in cooperation with Phil Hsueh (Florida State University) and Holland, are to understand the physics of the mixing process and to test predictive models. Their work involves the application of a primitive-equation eddy-resolving circulation model to the Kuroshio/East China Sea System in the region extending from Taiwan to the southern Japanese islands (119–135°E, 22–35°N). The model design includes realistic geometry and bottom topography, temperature and salinity as state variables, and open boundary conditions. This model configuration is well suited to the team's objectives of understanding the mesoscale dynamics governing the mixing between the Kuroshio and the East China Sea and testing different hypotheses about the mixing process.

A simple test-case integration of the model has already yielded two interesting results. In this experiment, the annual mean wind-stress field was used to force a barotropic ocean with closed boundaries for one year. The first result is that the barotropic transport streamfunction will come into equilibrium with the topography within a period of one-half year. Secondly, the annual mean wind stress over this region drives a cyclonic gyre, in distinction to the larger anticyclonic subtropical gyre of the North Pacific that gives rise to the Kuroshio. This cyclonic circulation dominating the flow in the model domain suggests a simple explanation of the mixing phenomena observed along the shelf break. The pattern of the streamlines is intensified near the northeast corner of Taiwan, suggesting a highly localized point of outflow from the East China Sea. In contrast, the streamlines are relatively broad and weak everywhere else, suggesting that the entire shelf break north of Taiwan participates in yielding a sluggish inflow of "off-shelf" water into the East China Sea. These results are interesting, as far as they go, but should not be taken as final, since the group's understanding of the mixing phenomena will evolve as they do more realistic experiments with the full baroclinic model, and more observations become available.

On climatic time scales the thermohaline circulation, the large-scale meridional overturning circulation driven by surface heat and freshwater fluxes, is crucial in understanding the role of the world ocean in global climate variability. Indeed, paleo-oceanographic evidence appears to indicate that the meridional circulation of the North Atlantic has changed dramatically since the last ice age. Furthermore, recent modeling experiments appear to indicate that the thermohaline circulation exhibits multiple equilibrium solutions. At the same time, simple models and experiments have shown that the growth and decay of sea ice can introduce variability into the upper polar oceanic heat and saline budgets. This is precisely the region of the ocean where deep water formation occurs (i.e., the sinking branch of the meridional circulation) and it is expected that this variability could affect the thermohaline circulation, thus having important consequences for global climate change. David Darr, in collaboration with scientists in the Oceanography Section (CGD), is exploring a range of simple models of the upper polar ocean with thermodynamic sea-ice models in an attempt to understand how these upper ocean processes affect the long-term variability and stability of the thermohaline circulation.

Measurements

Recent work in global change research has demonstrated the potential importance of the biota in affecting climate systems. In particular, peatland vegetation is thought to have a significant influence on trace gas chemistry and moisture content of the troposphere. For instance, peatland sources of methane (a radiatively important trace gas which is currently rising at about 1% per year) are known to be important, but have been poorly quantified. Lee Klinger used a combination of field, laboratory, and modeling studies in collaboration with numerous scientists in the Atmospheric Chemistry Division, or ACD (Patrick Zimmerman, Stanley Tyler, Alan Fried, Alan Hills, James Greenberg), and CGD (Starley Thompson); various university students (David Goldblum and Jill Walford, both at the University of Colorado); and other scientists (Nigel Roulet of York University, England, and Thomas Moore of McGill University, Montreal, Quebec, Canada) to characterize and quantify the feedbacks between peatland vegetation and climate. Working closely with Zimmerman, Klinger coordinated NCAR's participation in the Canadian Northern Wetland Study (NOWES), a large collaborative effort by numerous Canadian universities and U.S. agencies to examine the role of northern wetlands in climate change. He led field expeditions to Schefferville, Quebec, and Moosonee, Ontario, in the summers of 1989 and 1990, respectively, to examine the relationship between peatland succession and carbon trace gas emission rates.

Klinger conducted microcosm studies on the factors controlling methane emissions in bogs using two small bogs transported from Minnesota. During the summer of 1990, methane emissions were monitored regularly along with soil water pH to establish baseline data for future manipulations. These manipulations will involve examining the effects of water table height, soil water pH, rain water pH, soil redox potential, and soil temperature on methane emission rates.

Work to develop and test several new sampling and detection instruments for measuring methane emissions from peatlands and rice paddies is near completion.

The circumpolar boreal forest may also play an important role in the global carbon cycle. The circumpolar boreal forest is the major global reserve of soil carbon and is second only to broadleaf humid forests in terms of carbon stored in live vegetation. Uptake and release of CO_2 by boreal forests may accound for approximately 50% of the seasonal amplitude in atmospheric CO_2 at Barrow, Alaska, and about 30% of the seasonal amplitude at Mauna Loa, Hawaii. In the Northern Hemisphere, the amplitude of seasonal atmospheric CO_2 concentrations has increased with time, and this may reflect increased metabolic activity of ecosystems in northern latitudes.

While there is much speculation on the role of boreal forests in the global carbon cycle, there are few flux measurements or theoretical models with which to confirm or deny this speculation. Gordon Bonan developed a model of daily ecosystem CO_2 flux that is based on an ecological, physiological, and biophysical understanding of the factors regulating productivity and decomposition in boreal forests. He has used this model to examine whether the boreal forests of interior Alaska are an annual source or sink of CO_2. His simulations indicate the forest landscape in interior Alaska is a significant annual sink of CO_2. If valid for other regions of the circumpolar boreal forest, Bonan's simulations indicate the circumpolar boreal forest absorbs 1–3 Gt C per year.

The atmospheric O_2/N_2 ratio is a conservative atmospheric tracer which is influenced by sources and sinks of O_2 from the land biosphere, the ocean surface, and fossil fuel burning. Measurements of the oxygen/nitrogen ratio would address several important questions, including: (1) What is the net source of carbon dioxide from the land biopshere? (2) What is the magnitude of "new" biological production in the surface waters of the ocean?

Last year Ralph Keeling reported seven months of semicontinuous measurements of the O_2/N_2 ratio in air sampled at La Jolla, California, under "clean" conditions. This time series has now been continued with flask samples which have been analyzed using the interferometric method at NCAR. The data from these flasks confirm that the O_2/N_2 ratio varies seasonally, and that the amplitude of the seasonal variation is twice as large as expected based on the exchange of O_2 with the land plants and soils. It appears that photosynthesis and respiration within the oceans must also contribute significantly to the seasonal variations. The oceanic oxygen fluxes required to explain the seasonal variation are quite large and may require revision of current estimates of "new" production in the oceans.

Considerable effort has been devoted to measuring the rate of exchange between the earth's surface and atmosphere of climatologically important trace gases. However, such measurements are still relatively difficult to make, and our knowledge of the spatial and temporal variability of the surface fluxes of many trace gases is quite limited. Kenneth Davis is attempting to develop a new method of measuring trace gas surface fluxes based on measurements of vertical mixing ratio gradients in the convective boundary layer. This method may make surveys of the surface fluxes of water vapor and ozone over large areas feasible through the use of airborne or satellite-borne differential absorption lidar (DIAL) instruments. This method would also make possible surface flux estimates derived from balloon or aircraft profiles of trace gas mixing ratio in the convective boundary layer.

Davis has tested this method on tether balloon measurements of isoprene collected during the Amazon Boundary Layer Experiments by Zimmerman and Greenberg (ACD). The isoprene fluxes estimated using this method agree well with previous estimates made using the same data set and two independent methods. Davis has begun an effort to verify observationally, using data from the First International Satellite Land Surface Climatology Project Field Experiment (FIFE), the flux-gradient relationship derived from Chin-Hoh Moeng and John Wyngaard's (MMM) large-eddy simulations on which the method is based. Robert Grossman (University of Colorado) is cooperating with the FIFE data analysis.

To resolve the three-dimensional kinematic structure of a hurricane remains a challenge for meteorologists even with the invention of airborne Doppler radar. With two penetrations through the hurricane center, an airborne Doppler radar can provide storm-scale flow fields, if one assumes that the hurricane is stationary and steady in several hours of time frame. Wen-Chau Lee, in association with Richard Carbone (Atmospheric Technology Division, or ATD) and Frank Marks (NOAA), developed an algorithm that can extract the mean-first-order quantities, such as vorticity and divergence, from just one pass through the hurricane center. By taking advantage of the special scanning geometry of the airborne Doppler radar, harmonic analysis performed on the radial velocities that lie on a circle from the hurricane center permits the recovery of the tangential wind and the mean radial wind.

This algorithm has been tested on Hurricane Gloria (1985). The first three harmonics of the wind fields on the flight level have been successfully retrieved. Currently, Lee is testing the possibility of extending this algorithm to the entire hurricane.

With the development of the Next Generation Weather Radar (NEXRAD), single-Doppler radar observations will extensively cover the United States. These observations provide along-beam velocity and reflectivity with a horizontal spatial resolution of less than 1 km and a temporal resolution of a few minutes. The use of these data for initialization of storm prediction models and for sampling the eddy structure of boundary-layer flows requires a retrieval from the single-Doppler data of the other two components of velocity and temperature.

Juanzhen Sun, as part of her thesis research for the University of Oklahoma and in collaboration with Douglas Lilly (University of Oklahoma) and Moeng, used an optimal control method for such retrieval. This method uses a dynamic model, and attempts to determine the initial conditions of the unobserved flow and thermodynamic fields that have generated the time sequence of observed fields. A set of adjoint equations is constructed to determine the sensitivity of the cost function to initial state errors in those quantities that are not observed. The initial state variables are then adjusted to minimize those errors. Results from 13 identical-twin experiments show that the method is able to determine the spatial structures of the unobserved velocity components and temperature effectively; the performance is enhanced by the use of a temporal smoothness constraint. The method is not sensitive to moderate-amplitude random observational errors.

The turbulent kinetic energy (TKE) balance describes a fundamental quantity of turbulence and is used in almost every turbulence study. It is not yet possible to formulate theoretical relationships for the various terms in this balance, so it is necessary to obtain them empirically. Several experimental programs over the last 20 years have measured some of the terms, but none has measured all and the published results do not agree.

This year, Steven Oncley led a team of five investigators to measure all of the terms of the budget directly. The FLAT (Full Look at TKE) experiment was the first use of the new ASTER (Atmosphere-Surface Turbulent Exchange Research) facility developed by ATD. The standard ASTER system is able to measure the shear, buoyancy, and turbulent transfer terms. Two user sensors, a fast-response static pressure sensor developed by Al Bedard (NOAA) and a high-frequency hot-wire anemometer, were added to the study to measure the pressure transport and dissipation terms, respectively. Nine PAM II (portable automated mesonet) stations were deployed around the site in southeastern Wyoming to check for horizontal homogeneity, and both acoustic and ultrahigh-frequency profilers were used to obtain the height of the boundary layer. Several other investigators took advantage of this "ideal" experiment to make related measurements. The field program was from September to November to obtain a full range of atmospheric stability, including neutral stability. During this period there were three snowfalls which gave a change in surface roughness. Oncley will spend a good portion of the next two years analyzing the approximately 90 Gbytes of data from this experiment.

Garland Upchurch completed his reconstructions of the latest Cretaceous paleogeography and paleovegetation for use in simulations of paleoclimate during the mass extinction at the end of the Cretaceous. Paleogeographic reconstructions represent a consensus of different plate tectonic reconstructions and land-sea distributions 66 million years before present. Most paleogeographies are similar to those being produced by the Paleogeographic Atlas Project (University of Chicago), but there are some differences in land-sea distribution and uncertainties regarding the placement of regions such as the Antarctic Peninsula.

Paleovegetational reconstructions are based on the physiognomy of plant megafloral assemblages, evaporite and coal distributions, and herbivore browse profiles. They differ from those of the Paleogeographic Atlas Project in several important respects, most notably in the distribution of Mediterranean forest and desert vegetation, and in proposing widespread distribution of subhumid evergreen forests that existed under little seasonality of precipitation. Important vegetational parameters for climate modeling, such as leaf area index and stomatal resistance, have been inferred by using values for the most similar extant vegetation type. Modifications of these parameters to account for higher CO_2 levels during the latest Cretaceous have not been made, in part because the response of modern plant communities to elevated CO_2 is still not well understood.

Growing evidence supports the hypothesis that humans are in the process of inadvertently modifying the earth's climate by increasing the atmospheric concentrations of CO_2 and other radiatively active trace gases. The present human-induced climatic change, often referred to as the greenhouse effect, is different from natural changes because of its unprecedented pace and our incomplete knowledge of its consequences. As some scientists put it, humanity is performing on itself a "global experiment" that may entail a number of surprises.

Potential changes in the behavior of atmosphere/biosphere interactions could affect atmospheric dynamics, local and regional hydrology, global biogeochemistry, and, therefore, human societies. Philippe Martin examined five aspects of climate/vegetation interactions in his thesis. The main part of his thesis focused on the response of forests to climatic changes using a model treating the physics of energy and water exchange in detail. Because the Energy, water, and momentum eXchange and Ecological dynamics (EXE) model couples the land-surface processes and the ecological dynamics of forests of the northeastern America, new insights were gained into the behavior of forests, in general, and the possible consequences of a greenhouse effect on forest hydrology and vegetation succession, in particular.

Tropical forest soils are the largest known source of atmospheric nitrous oxide and a small sink for methane. Both nitrous oxide and methane are greenhouse gases whose atmospheric concentrations are increasing rapidly. Tropical forest soils also emit sufficient quantities of nitric oxide (NO) to affect regional tropospheric oxidant balance. Changes in the atmospheric concentrations of these biogenic gases has been tentatively linked to tropical deforestation.

Michael Keller investigated the effects of deforestation on the soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane at the La Selva Biological Station in Costa Rica. The study was planned to quantify soil-atmosphere gas fluxes from the dominant land uses (rain forest and pasture) in this region and to identify the controlling mechanisms, both biological and physical, for these fluxes. Keller used field soil enclosure techniques to quantify gas fluxes. In collaboration with William Reiners (University of Wyoming), Eric Davidson (NASA Ames Research Center), Tyler, and Zimmerman (both of ACD), Keller employed field manipulations (fertilization, irrigation, etc.), laboratory incubations, and isotropic tracers to identify biological controls of gas production and consumption. Inert gas tracers will be used to quantify the physical movement of soil gases. Preliminary data agree with past work on methane. Conversion of forest to pasture appears to diminish soil methane consumption. Contrary to studies at Brazilian sites, the nitrous oxide fluxes from pastures in Keller's current studies do not exceed forest soil emissions; in fact, they are an order of magnitude lower. Results for nitric oxide, the first of their kind, follow the same pattern as those for nitrous oxide.

John Mak undertook a study of radiocarbon in atmospheric carbon monoxide as part of his thesis work at the Scripps Institution of Oceanography. The work is being carried out at the Institute of Nuclear Sciences in New Zealand.

For this study, Mak developed an aircraft air sampling system that collects large, whole air samples at high pressure. Vertical profiles were made in local regions to test the system, various improvements were made, and samples were prepared for accelerator mass spectrometer analysis.

Mak made flights over Antarctica and the South Pole to collect high latitude samples. Processing of these samples is under way.

Although the nitrogen dioxide (NO_2) photodissociative process $NO_2 + h\nu \rightarrow O(^3P) + NO$ has been investigated in the visible and ultraviolet regions for many years, a sound theoretical understanding of NO_2 photochemistry in the energy-deficient region (energies less than the dissociation limit) has not yet been achieved. A knowledge of the absorption cross sections (σ) and the quantum yields (ϕ) of NO_2 is required to calculate the photolysis rate coefficient of NO_2, yet neither parameter is well defined in the temperature and wavelength regions of atmospheric interest. Hence, Coleen Roehl has been involved in accurately measuring high-resolution, temperature-dependent σs and ϕs for NO_2 in the 390 to 410 nm range.

Initial work included designing specialized, temperature-controlled cells; gas handling systems; and inlet systems and interfacing them to a chemiluminescence detector. NOCl, which is used as an actinometer, was synthesized and its purity was analyzed with a BOMEM DA3.01 Fourier transform spectrometer. Temperature-dependent cross sections for NOCl were measured for the first time over a wide wavelength range using an EG&G photodiode array spectrometer. These measured cross sections exhibited an unexpectedly large temperature dependence throughout the wavelength range of interest.

Currently, Roehl is interfacing her experimental system to a computer. She expects to begin data acquisition shortly.

Because of the short atmospheric lifetimes of ethene and propene, the finding of these compounds in the remote marine environment suggests that some ocean regions produce these gases. Possible production methods include processes associated with photosynthesis and the photodecomposition of dissolved organic carbon (DOC). The studies outlined below could lead to a novel technique for estimating primary production, quantify a removal process for DOC, and provide insight into the photochemical controls of the remote marine atmosphere.

Kevin Harrison's research on ethene and propene in the marine environment consists of three experimental studies: variations of atmospheric ethene and propene near the California Current, variations of dissolved ethene and propene in a water column, and seasonal variations of dissolved ethene and propene in lower Cook Inlet, Alaska. The atmospheric study attempts to link high atmospheric concentrations of ethene and propene to productivity in the ocean and processes affecting air-sea exchange. The water column study tries to elucidate and evaluate the contributions of different production mechanisms, such as primary production and photodecomposition of DOC. The seasonal study attempts to establish a quantitative relationship between ethene and propene production and indicators of productivity.

The atmospheric samples taken near the California Current have shown elevated ethene and propene concentrations for air masses that have moved over regions of high oceanic productivity. For the water column study Harrison built and tested a light hydrocarbon seawater extraction system and analyzed 150 samples. He was able to show that subsurface ethene and propene maxima occur near the highest levels of productivity.

In the spring arctic troposphere, ozone concentrations have been found to decrease at a very rapid rate and have been found to fluctuate in antiphase to bromine species. However, a mechanism to explain the anticorrelation by photolysis of bromoform, which is at high concentrations in the arctic spring, to provide bromine atoms to react catalytically with ozone has not been satisfactory because the slow bromoform photolysis leads to slow ozone destruction. Shao-Meng Li, in cooperation with John Winchester (Florida State University) and Jack Calvert (ACD), focused on the mechanism for the ozone depletion. By direct field measurements at the NOAA Geophysical Monitoring for Climate Change station at Barrow, Alaska, in the spring seasons in 1986 and 1989, he found that ozone in the arctic may interact not only with bromine compounds but also with nitrogen compounds. He detected nitrous acid (HNO_2) in gas phase, particles, and snow. HNO_2 is a hydroxyl (OH) source as it undergoes photodissociation to OH and NO. Its concentrations in the arctic spring indicate that OH radical concentrations could be one to two orders of magnitude higher than previously thought. This level of OH radical could initiate a whole series of reactions, but most importantly could release bromine (Br) atoms from a hydrogen bromide reservoir. At the levels of OH radical sustained by HNO_2 photolysis, Br atom production rate is about ten times higher than from bromoform photolysis, thereby providing Br atoms to the Br-ozone catalytic reaction cycle. In addition, HNO_2 photolysis also releases NO, which reacts with ozone rapidly and provides a direct path for ozone destruction. This may explain, at least in part, the sudden ozone disappearance in spring arctic troposphere and its connection to bromine species. However, the formation of HNO_2 in the arctic is not well known, although there is evidence that heterogeneous pathways may be important.

Over the last 15 years, ground-based atmospheric radars have played an ever-increasing role in the study of middle and lower atmospheric dynamics. Background wind and turbulence can now be derived with fine height and temporal resolution. Generally, one can divide these radars into two groups: Doppler radar and spaced antenna (SA) systems. Both techniques derive their information from radar echoes off irregularities in the refractive index of the atmosphere. These irregularities arise from fluctuations in temperature, humidity, and pressure in the troposphere-stratosphere regions. In both regions, echoing mechanisms can involve turbulence scattering as well as reflection and scatter from stratified structures.

During his Ph.D. thesis research in 1986-88 supported by a High Altitude Observatory research assistantship, Joel Van Baelen performed a detailed comparison of the different atmospheric radar techniques, analyzed how the dynamics of the atmosphere influenced their results, and also developed a new interferometric technique that offers great potential for unbiased measurement of the vertical veolcity and for analysis of the atmospheric fluxes. His research was performed in collaboration with the Radio Atmospheric Science Center, Kyoto University, using the VHF middle and upper atmosphere radar and focused on the stratosphere and lower stratosphere.

Presently an ASP postdoctoral fellow, Van Baelen is pursuing his initial research along two paths. First, in collaboration with ATD, he is doing simulations to investigate the feasibility and possible merits of a UHF interferometric system to be tested in the scope of the integrated sounding system project. Second, visiting at Arecibo Observatory, he is involved in the study of mesospheric dynamics and gravity waves using data from a spaced antenna system and applying the different algorithms he developed.

Thomas Downing conducted research on African vulnerability to famine, in the context of climatic, demographic, and economic variations. A major review of the literature contributed to the formation of concepts of vulnerability, which he subsequently applied to the U.S. Agency for International Development's Famine Early Warning System in Burkina Faso, Chad, Ethiopia, Mali, Mauritania, and Niger. Vulnerable areas can be readily identified at the start of the growing season and monitored for significant changes such as poor rainfall, pestilence, and civil strife. By focusing on a wide definition of vulnerability, famine monitoring can be expanded beyond the limited focus on drought and crop failure to encompass entitlement losses and structural issues. Vulnerability assessments form a link between emergency responses and development planning, by identifying areas and socioeconomic groups that experience recurrent low food security.

Communities in mountain regions throughout the world are increasingly becoming dependent on tourism. Many of the resources necessary for tourism are sensitive to variability in climatic variables. To provide a background to the assessment of such sensitivity, Martin Price undertook a review of pertinent literature from mountain regions around the world. Price also compiled data sets of snow cover, snowfall, and other meteorological parameters for the mountains of Colorado. These data may be used to define historical variability, identify zones with similar characteristics for snowfall and snowmaking, and assess the sensitivity of the Colorado ski industry and the communities that depend on it to climate variability and long-term change.

Observations of sea surface height with a sea surface altimeter may allow oceanographers to reconstruct mesoscale eddy variability with sufficient accuracy to make possible data assimilation in ocean circulation models. Eric Chassignet, making use of a multilevel model of the Gulf Stream system that has realistic spatial and time scale behavior, inquired into the ability of optimal interpolation techniques to map the sea surface height variability field, given a variety of satellite orbit scenarios.

Chassignet generated data sets of sea surface height along the tracks of various satellites from the numerical model for a period of two years. He then interpolated this model data to the model grid using the successive correction scheme. The ability of each altimeter to map the mesoscale eddy field of the numerical model was then examined as a function of its coverage and of the choice of the autocorrelation functions. These mapped data were then assimilated into the numerical model and the ability of each satellite to reconstruct the four-dimensional picture of the circulation discussed.

Overall root-mean-square errors over the whole domain do not differ much among satellites, so that each satellite's capability need be viewed in light of the topic to be studied. For example, GEOSAT, with a 17-day repeat period, is able to keep track of Gulf Stream rings even if they strongly deform in shape between observations. Updated information is provided in the opposite sense of the ring's propagation. On the other hand, ERS-1, with a repeat period of 35 days (subcycle of 16 days), could lose completely any information on the ring. Finally, TOPEX-POSEIDON, with a repeat period of 10 days, because of the large distance between adjacent tracks, is not able to keep track of a ring as it propagates westward. Tracking of oceanic rings is thus strongly dependent on the altimeter's orbit characteristic. High resolution in space and an eastward filling pattern are preferable.

Summer Colloquium

ASP and MMM hosted a summer colloquium entitled Mesoscale Data Assimilation. Twenty-three lecturers from 13 institutions spoke during the sessions, which were coordinated by Kuo (MMM) and Thomas Schlatter (NOAA). The 55 graduate and postgraduate students and professionals who participated in the colloquium represented 32 institutions.

Global Change Instruction Program

John Firor (ASP) and Winchester (Florida State University) hosted a three-day workshop for 25 participants from 14 institutions. These participants revised draft course materials tested in the classroom during the 1989–90 school year. Additional courseware modules were identified and assigned to the participants to expand the selection. A final workshop to complete the materials will be held in the summer of 1991.

Education and Tour Program

Although education has been an important part of NCAR's mission since its inception, only in the last five years has there been a formal program at NCAR to address the education needs of students and teachers of grades K-12. These people began making use of NCAR's resources as soon as the Education Program was established at NCAR in the fall of 1986. The numbers of contacts have risen steadily since then, with about 5000 teacher and student visits in each of the last two years. All of this activity recently culminated in the writing of NCAR's first education proposal, being submitted to the NSF Teacher Enhancement Program. When it is funded, NCAR will be able to bring teachers from selected states across the nation to Boulder for three consecutive summers to provide current and background materials about the atmospheric sciences.

To respond to this level of education, NCAR's resources, both staff and products, have been utilized in four primary ways: (1) through visits from schoolchildren, who come to learn how some aspect of science studied in school is carried out at NCAR; (2) through visits from teachers, who come individually throughout the year and collect information while here, or through organized in-service visits for groups of teachers, in which NCAR organizes programs tailored to those teachers' interests; (3) through filling information requests (calls, letters, visits) for scientist assistance, literature on special topics, audiovisual materials, or other resources needed to satisfy an individual or class activity; and (4) through distribution of products and programs that help explain NCAR's research to young audiences, for example, NCAR's weather exploration movie for children, which is being distributed nationally; an after-school weather course, developed in collaboration with the Science Discovery Program of the University of Colorado, which is taught to local school children; and the information packets the Education Program has put together on various topics for distribution.

Outreach by NCAR into the educational community—both in Colorado and nationally, as contacts develop—is also important. The Education Program makes it a point to be represented at science, teacher, and environmental meetings throughout the year. These meetings provide valuable two-way networking opportunities for NCAR and expand what the center has to share with others. Within the local education community, NCAR has increasingly offered itself as a resource. The Education Program is part of two education-oriented community organizations, and supports numerous events such as local school science fairs, the district science fair, National Science and Technology Week, and annual Earth Day activities. For the last two years NCAR has awarded grants to Boulder teachers to accomplish classroom science projects during the school year, and last summer provided a stipend to allow a local teacher the opportunity to spend six weeks working in one of NCAR's science labs and participating in the related field research.

With the national mandate to improve science education, NCAR will continue to develop these and related activities. Such activities can supplement and enrich traditional school courses and materials and help motivate the next generation of scientists. By participating as an organization and as individuals, NCAR and its staff can play an important role in achieving this national goal. We can help assure that the information conveyed to teachers and schoolchildren is valid and appropriately presented, and at the same time make a useful and important contribution to the community and to the nation.

Staff and Visitors

Staff

Advanced Study Program

John Firor (director)
Barbara McDonald
Judy Miller (from 5/14/90, 80%)
Elizabeth O'Lear (to 7/1/90, 50%)
Walter Orr Roberts (to 3/12/90)
Ursula Rosner (to 2/28/90, 50%)

Information Services

Anatta (75%)
Marie Boyko (director)
Milli Butterworth
Steven Davis (25%)
Marian Goodrich
Robert Henson (75%)
Rene Munoz (director, Education and Tour Program)
Juanita Razo
Lucy Warner(75%)

Media Relations

Anatta (25%)
Joan Vandiver Frisch (director)

Graduate Research Assistants

Antonietta Capotondi; Massachusetts Institute of Technology; assimilation of altimeter data into ocean circulation models; William Holland, CGD

David Darr; University of Colorado; thermohaline circulation/geophysical fluid dynamics; William Holland, CGD

Kenneth Davis; University of Colorado; measurement of chemical fluxes at the earth's surface using mixed-layer gradients; Patrick Zimmerman, ACD

Anne DeRudder; Belgian Institute for Space Aeronomy; natural and anthropogenic perturbations of the ozone layer; Guy Brasseur, ACD

Michael Dixon; University of Colorado; nowcasting and short-term forecasting of convective storm phenomena, particularly rainfall; Brant Foote, RAP

Kevin Harrison; University of California, San Diego; study of the geochemistry of ethene and propane in the marine environment; Patrick Zimmerman, ACD

Michael Keller; Princeton University; biological sources and sinks of atmospheric methane in tropical environments; Stanley Tyler, ACD

John Mak; Scripps Institution of Oceanography; quantitative determination of the marine emissions of ethylene and propylene; identification of the sources of these emissions; Patrick Zimmerman, ACD

Philippe Martin; University of California, Berkeley; biosphere-mediated hydrological feedbacks to a CO_2-induced climate change; Robert Dickinson, CGD

Coleen Roehl; University of California, Santa Barbara; gas-phase chemistry; Jack Calvert, ACD

John Schultz; Florida State University; numerical model of the western boundary of the North Pacific; William Holland, CGD

Ilana Stern; Massachuetts Institute of Technology; observational studies of the general circulation; Kevin Trenberth, CGD

Juanzhen Sun; University of Oklahoma; practical recovery of wind and temperature fields from single Doppler radar data; Chin-Hoh Moeng, MMM

Andrew Turnipseed; University of Colorado; measurement of gas-phase rate constants for reaction of ClO and BrO; Jack Calvert, ACD

Cynthia Twohy-Ragni; University of Washington; study of cloud and aerosol chemistry, instrument development; William Cooper, ATD/MMM

Davinder Virk; University of Houston; numerical simulation of vortex reconnection; Robert Kerr, MMM

Wei Wang; Pennsylvania State University; genesis of Tibetan Plateau mesoscale vortices; Ying-Hwa Kuo, MMM

Postdoctoral Fellows

Gordon Bonan; University of Virginia; forest dynamics modeling, biosphere-atmosphere interactions

Teresa Campos; Purdue University; application of the fluorometric formaldehyde assay to the study of the oxidative capacity of the atmosphere

Eric Chassignet; University of Miami; general oceanic circulation (including oceanic rings) from numerical modeling and observational points of view

Ming-Dean Cheng; University of California, Los Angeles; prediction of mesoscale convective organization and its impacts on the cumulus large-scale interaction

Marie Dahleh; University of Chicago; midlatitude cyclone development

Chris Davis; Massachusetts Institute of Technology; cyclogenesis diagnosis with potential vorticity: carrying out numerical integrations of a primitive equation model on cases studied

Thomas Downing; Clark University; hunger vulnerability and food security issues in Africa in relation to prospects of long-term climate change and short-term climate variability

Michael Goodman; New York University; theoretical and numerical MHD studies of the sun's atmosphere

Sue Ellen Haupt; University of Michigan; application of nonlinear wave equations to large-scale atmospheric flows

Peter Hess; University of Washington; atmospheric dynamics and tracer transport processes

Ralph Keeling; Harvard University; atmospheric oxygen measurements

Michael Keller; Princeton University; nitrous oxide emissions in Costa Rica

Lee Klinger; University of Colorado; role of bryophyte paludification in climate change

Eugene Lavely; Massachusetts Institute of Technology; helioseismology

Wen-Chau Lee; University of California, Los Angeles; studies of hurricane rain bands and vertical momentum fluxes using a single Doppler radar

Marie-Pascale Lelong; University of Washington; gravity wave–vortical mode nonlinear interactions

Shao-Meng Li; Florida State University; geochemistry of organic acids, bromine species, and aerosols

Eugene McCaul; University of Oklahoma; convective storm structure and dynamics

Linda Mearns; University of California, Los Angeles; analysis of the frequency of extreme climatic events under climatic change, and technological and climatic impacts on agricultural production

Graham Murphy; University of Sydney, Australia; determination of magnetic fields in sunspots through Stokes profile inversion

Raymond Najjar; Princeton University; the ocean's role in the climate system: relative role of ocean circulation, biology and chemistry in controlling atmospheric carbon dioxide

Steven Oncley; University of California, Irvine; surface-layer flux measurement techniques

Martin Price; University of Colorado; assessment of the sensitivity of mountain communities and societies to climate variability and change

Jeffrey Proehl; University of Washington; equatorial wave–mean flow interactions, coastal and estuarine dynamics

Sue Schauffler; Texas A&M University; investigation of the marine sources of methyl bromide and bromoform

William Skamarock; Stanford University; geophysical fluid dynamics relating to atmospheric flows in scale interaction

Christopher Snyder; Massachusetts Institute of Technology; large-scale dynamics, baroclinic instability, and strong interactions between motions of different scales

Olivier Thual; University of Nice, France; fluid mechanics instabilities: nonlinear dynamics and direct numerical simulations

Garland Upchurch, Jr.; University of Michigan; paleoclimate and mass extinction

Joel Van Baelen; University of Colorado; concurrent spaced antenna techniques for wind profiling and atmospheric dynamics studies with Doppler VHF radars

Tomislava Vukicevic; University of Utah; predictability of small-scale atmospheric motions using three-dimensional numerical models

Jeffrey Weiss; University of California, Berkeley; nonlinear dynamics, chaotic advection, and geophysical flows

Participants in Summer Colloquium

Kazumasa Aonashi, Meteorological Research Institute, Ibaraki, Japan

Nancy Baker, Naval Oceanographic and Atmospheric Research Laboratory

Michael Baldwin, University of Oklahoma

Jian-Wen Bao, Pennsylvania State University

Daniel Birkenheuer, National Oceanic and Atmospheric Administration

Trevor Carson, California State University

Ching-Hsun Chen, Central Weather Bureau of Taiwan

Wen-Mei Chen, Central Weather Bureau of Taiwan

Robert Cohen, Drexel University

Jeffrey Copeland, Colorado State University

Norman Donaldson, Atmospheric Environment Service, Canada

Sharon Douglas, Systems Applications, Inc.

Ronald Errico, NCAR (CGD)

Jerome Fast, Iowa State University

Richard Franke, Naval Postgraduate School

Pierre Gauthier, Atmospheric Environment Service, Dorval, Canada

Anna Ghelli, Paul Scherrer Institute, Basel, Switzerland

Yong-Run Guo, NCAR (MMM)

Zitian Guo, National Meteorological Center of China, Beijing, P.R. China

Dewey Harms, North Carolina State University

Bert Holtslag, NCAR (MMM)

Song-You Hong, Seoul National University

Toke Jayachandran, Naval Postgraduate School

Shi Jiang, University of California, Los Angeles

Mary Jordan, Naval Postgraduate School

Kayo Ide, Rutgers University

Dongsoo Kim, National Oceanic and Atmospheric Administration

Hee-Sang Lee, Meteorological Research Institute, Korea

Yong Li, University of Oklahoma

Shwu-Ching Lin, Central Weather Bureau of Taiwan

Simon Low-Nam, NCAR (MMM)

Peter Lynch, Irish Meteorological Service, Dublin

Dennis McNally, University of California, Davis

Richard Menard, McGill University, Canada

Patricia Miller, National Oceanic and Atmospheric Administration

Ranjit Passi, Institute for Naval Oceanography

Heribert Petry, University of Cologne, Germany

Saroja Polavarapu, Atmospheric Environment Service, Canada

Philip Politowicz, University of Wisconsin-Madison

Lennart Robertson, Swedish Meteorlogical and Hydrological Institute

Paul Schultz, National Oceanic and Atmospheric Administration

Meta Sienkiewicz, University of Oklahoma

John Snook, National Oceanic and Atmospheric Administration

David Stauffer, Pennsylvania State University

Peter Steinle, Bureau of Meteorology Rsearch Centre, Australia

Chung-Tsyr Terng, Central Weather Bureau of Taiwan

Kyozo Ueyoshi, Scripps Institution of Oceanography

Andrew Van Tuyl, National Oceanic and Atmospheric Research Laboratory

Johannes Verlinde, Colorado State University

Xiangqian Wu, University of Wisconsin

Xiaohua Wu, University of Wisconsin

Xiaoqing Wu, University of California, Los Angeles

Tai Yi Xu, University of Illinois at Urbana-Champaign

Kok-Seng Yap, Florida State University

Tien-Chiang Yeh, Naval Postgraduate School

Participants in Global Change Instruction Program

Eric Barron, Pennsylvania State University

Guy Brasseur, ACD

Arthur Few, Rice University

John Firor, ASP

David Fulker, UCAR

David Furbish, Florida State University

Judith Jacobsen, University of Wyoming

James Kasting, Pennsylvania State University

Lee Kump, Pennsylvania State University

Edward Laws, University of Hawaii

Joel Levine, NASA Langley Research Center

Nancy Marcus, Florida State University

Barbara McDonald, ASP

Mario Molina, Massachusetts Institute of Technology

Sharon Nicholson, Florida State University

Ken Osmond, Florida State University

Jozef Pacyna, Norwegian Institute for Air Research, Lillestrom

William Parker, Florida State University

David Schimel, Colorado State University

Glenn Shaw, University of Alaska

Daniel Simberloff, Florida State University

John Snow, Purdue University

John Streete, Rhodes College

Stanley Tyler, ACD

John Winchester, Florida State University

Publications

Refereed Publications

*BAKWIN, P.S., *S.C. WOFSY, *S.-M. FAN, M. KELLER, *S.E. TRUMBORE, and *J.M. DA COSTA, 1990: Emission of nitric oxide (NO) from tropical forest soils and exchange of NO between the forest canopy and atmospheric boundary layers. *J. Geophys. Res. 95*, 16,755-16,764.

—, —, —, —, 1990: Thermodynamic measurements under a wall cloud. *Mon. Weather Rev. 118*, 794-799.

BONAN, G.B. , 1990: Carbon and nitrogen cycling in North American boreal forests. I. Litter quality and soil thermal effects in interior Alaska. *Biogeochem. 10*, 1-28.

— , 1990: Carbon and nitrogen cycling in North American boreal forests. II. Biogeographic Patterns. *Can. J. of Forest Res. 20*, 1077-1088.

BUSINGER, J.A., and S.P. ONCLEY, 1990: Flux measurement with conditional sampling. *J. Atmos. Ocean. Techn. 7*, 349-352.

CHASSIGNET, E., *D. OLSON, and *D. BOUDRA, 1990: Motion and evolution of oceanic rings in a numberical model and in observations. *J. Geophys. Res. 95*, 22,121-22,140.

*CUSHMAN-ROISIN, B., E. CHASSIGNET, and *B. TANG, 1990: Westward motion of mesoscale eddies. *J. Phys. Oceanogr. 20*, 758-768.

DOWNING, T.E., 1990: Monitoring and responding to famine: lessons from the 1984-1985 food crisis in Kenya. *Disasters 14*, 204-229.

—, *S. LEZBERG, and *L. BERRY, 1989: Population change and environment in central and eastern Kenya. *Environ. Conser., 17*, 123-133.

FANTINI, M., 1990: The influence of heat and moisture fluxes from the ocean on the development of baroclinic waves. *J. Atmos. Sci. 47*, 840-855.

— , 1990: Nongeostropic corrections to the eigensolutions of a moist baroclinic instability problem. *J. Atmos. Sci. 47*, 1277-1287.

*FAUVE, S., and O. THUAL, 1990: Solitary waves generated by subcritical instabilities in dissipative systems. *Phys. Rev. Lett. 64*, 282-284.

— , *S. DOUADY, and — , 1990: Comment on "Parity-breaking transitions of modulated patterns in hydrodynamic systems." *Phys. Rev. Lett. 65*, 385.

GOODMAN, M.L., 1990: Scattering by a sphere with an anisotropic impedance boundary condition - MIE series solution and uniqueness conditions. *J. Opt. Soc. Amer. 7*, 1817-1823.

GRABOWSKI, W.W., and P.K. SMOLARKIEWICZ, 1990: Monotone finite-difference approximations to the advection-condensation problem. *Mon. Weather Rev. 118*, 2082-2097.

HALLETT, J., *J.G. HUDSON, and A. SCHANOT, 1990: Student training in facilities in atmospheric science: A teaching experiment. *Bull. Am. Meteorol. Soc. 71*, 1,637-1,641.

HESS, P., 1990: Variance in trace constituents following the final stratospheric warming. *J. Geophys. Res. 95*, 13,765-13,779.

*KAUFFMAN, E.G., G.R. UPCHURCH, JR., and *D.J. NICHOLS, 1990: The Cretaceous-Tertiary boundary interval at south Table Mountain, near Golden, Colorado. In *Extinction Events in Earth History* (E.G. Kauffman and O.H. Walliser, Eds.), Springer Verlag, Lecture Notes in the Earth Sciences No. 30, 365-392.

KELLER, M., *M.E. MITRE, and *R.F. STALLARD, 1990: Consumption of atmospheric methane in soils of central Panama: Effects of agricultural development. *Glob. Biogeochem. Cycles 4*, 21-27.

KLINGER, L.F., 1990: Global patterns in community succession. 1. Bryophytes and forest decline. *Memoirs of the Torrey Botanical Club 24*, (a monograph series), 1-50.

— , *S.A. ELIAS, *V.M. BEHAN-PELLETIER, and *N.E. WILLIAMS, 1990: The bog climax hypothesis: fossil arthropod and stratigraphic evidence in peat sections from southeast Alaska. *Holarctic Ecol. 13*, 72-80.

LI, S.-M., and J.W. WINCHESTER, 1989: Geochemistry of organic and inorganic ions of late winter Arctic aerosols. *Atmos. Environ. 23*, 2401-2415.

—— , —— , 1990: Haze and other aerosol components in late winter Arctic Alaska, 1986. *J. Geophys. Res. 95*, 1797-1810.

—— , —— , 1990: Particle size distribution and chemistry of late winter Arctic aerosols. *J. Geophys. Res. 95*, 13,897-13,908.

——, and ——, 1989: Resolution of ionic components of late winter Arctic aerosols. *Atmos. Environ. 23*, 2387-2399.

—— , —— , and *J.M. PACYNA, 1990: Arctic aerosol sulfur with silicon, but no aluminum: evidence for long range transport of coal smoke. In *Proc. of the International Conference on Global and Regional Atmospheric Chemistry*, Beijing, China, May 3-10, 1989. (L.E. Newman, W.X. Wang, and C.S. Kiang, Eds.). U.S. Department of Energy, 150-160.

—— , —— , *J.D. KAHL, *S.J. OLTMANS, *R.C. SCHNELL, AND *P.J. SHERIDAN, 1990: Arctic boundary layer ozone variations associated with nitrate, bromine, and meteorology: A case study. *J. Geophys. Res. 95*, 22,433-22,440.

MARTIN, P., 1989: The significance of radiation in coupling vegetation and the atmosphere. *Ag. For. Meteor. 49*, 45-54.

MEARNS, L.O., S. SCHNEIDER, S. THOMPSON, and L. McDANIEL, 1990: Analysis of climate variability in general circulation models: comparison with observations and changes in variability in 2 x CO_2 experiments. *J. Geophys. Res. 95*, 20,469-20,490.

MORRISETTE, P., 1989: The evolution of policy responses to stratospheric ozone depletion. In *Nat. Res. J. 29*, 793-820.

POE, C.H., *S.P. OWOCKI, and *J.I. CASTOR, 1990: The steady state solutions of radiatively driven stellar winds for a non-Sobolev, pure absorption model. *Astrophys. J. 358*, 199-213.

PRICE, M.F., 1990: Humankind in the biosphere: the evolution of international interdisciplinary research. *Glob. Environ. Change: Human and Policy Dimen. 1*, 3-13.

—— , 1990: Temperate mountain forests: common-pool resources with changing, multiple outputs for changing communities. *Nat. Res. J. 30*, 685-707.

PROEHL, J.A., 1990: Equatorial wave-mean flow interaction: the long Rossby waves. *J. Phys. Oceanogr. 20*, 274-294.

ROTUNNO, R., and M. FANTINI 1989: Petterssen's "Type B" cyclogenesis in terms of discrete neutral Eady modes. *J. Atmos. Sci. 46*, 3599-3604.

SMOLARKIEWICZ, P.K. and W.W. GRABOWSKI, 1990: The multidimensional positive definite advection transport algorithm: Nonoscillatory option. *J. Comput. Phys. 86*, 355-375.

*TRUMBORE, S.E., M. KELLER, *S.C. WOFSY, and *J.M. DA COSTA, 1990: Measurements of soild and canopy exchange rates in Amazon rain forest using 222Rn. *J. Geophys. Res. 95*, 16,865-16,873.

TURNIPSEED, A.A., *J.W. BIRKS, and J.G. CALVERT, 1990: Kinetics of the BrO + BrO Reaction. *J. Phys. Chem. 94*, 7477.

VAN BAELEN, J.S., *T. TSUDA, A.D. RICHMOND, *S.K. AVERY, *S. KATO, *S. FUKAO, and *M. YAMAMOTO, 1990: Comparison of VHF Doppler beam swinging and spaced antenna observations with the MV radar: first results. *Radio Sci. 25*, 629-640.

VUKICEVIC, T., 1990: The influence of topographic forcing upon predictability in the limited-area model. In Preprint Vol., *Fifth Conference on Mountain Meteorology*, Boulder, Colo., 25-29 June 1990. American Meteorological Society, Boston, Mass., 125-127.

——, and R.M. ERRICO, 1990: The influence of artificial and physical factors upon predictability estimates using a complex limited-area model. *Mon. Weather Rev. 118*, 1460-1482.

WEISS, J.B., and *E. KNOBLOCH, 1990: A stochastic return map for stochastic differential equations. *J. Stat. Phys. 58*, 863-883.

WELLS, L.E., 1990: Holocene history of the El Niño phenomenon as recorded in flood sediments of coastal Peru. *Geology 18*, 1134-1137.

Other Publications

ATLAS, E.L., and S. SCHAUFFLER, 1990: Concentration and variation of trace organic compounds in the north Pacific atmosphere. In *Long Range Transport of Pesticides*, (D. Kurtz, Ed.), Lewis Publishers, Inc., Chelsea, Mich., 161-183.

CHASTEEN, T.G., 1990: *Fluorine-induced Chemiluminescence Detection of Biologically Methylated Tellurium, Selenium, and Sulfur Compounds and Methyldithiocarbhydrazide as a Formaldehyde Derivatization Reagent.* Cooperative Thesis NCAR/CT-129, NCAR, Boulder, Colo., 137 pp.

DOWNING, T.E., 1989: African Household food security: What are the limits of available coping mechanisms in response to climatic and economic variations? Paper presented to the *First Workshop of the IGU Study Group on Famine Research and Food Production Systems*, Freiburg, FRG, 11-14 November 1989.

—, 1990: *Assessing socioeconomic vulnerability to famine: frameworks, concepts, and applications.* A report to the U.S. Agency for International Development (AID), Famine Early Warning System (FEWS) Project. AID/FEWS, Washington, D.C. and World Hunger Program, Brown University, Providence, Rhode Island.

— , and *M.L. PARRY, 1990: Report: *Proposed methodology for the vulnerable regions component of the Climate Change and International Agriculture project. Potential effects of climate change on vulnerability to food shortage and food poverty in selected developing countries.* Atmospheric Impacts Research Group, School of Geography, University of Birmingham, Birmingham, U.K.

*JACOBSON, H.K., and M.F. PRICE, 1990: A framework for research on the human dimensions of global environmental change. *ISSC/UNESCO Social Sciences Series No. 3*, International Social Science Council, Paris, France, 13-14.

*KATES, R.W., *R. CHEN, M.F. PRICE, *J.X. KASPERSON, *E. MESSER, and *S. MILLMAN, 1989: *The Hunger Report: Update 1989.* Alan Shawn Feinstein World Hunger Program, Brown University, Providence, R.I.

KELLER, M.M., 1990: *Biological Sources and Sinks of Methane in Tropical habitats and Tropical Atmospheric Chemistry.* Cooperative Thesis NCAR/CT-126, NCAR, Boulder, Colo., 216 pp.

LI, S.-M., and J.W. WINCHESTER, 1989: Arctic aerosol sulfur with silicon, but no aluminum: evidence for long range transport of coal smoke. Abstract of paper for presentation at the *International Conference on Global and Regional Environmental Atmospheric Chemistry*, Beijing, China, 3-10 May, 1989, U.S. Department of Energy.

— , and — , 1989: Components of aerosol sulfur in the winter Arctic atmosphere. Abstract of oral presentation at the 1989 AGU Spring Meeting, Baltimore, Md. *EOS (Trans. Am. Geophys. Union) 70*, 287.

— , and — , 1988: Nitrate interference with a bromine-ozone anticorrelation in the late winter Arctic at Barrow, Alaska. Abstract of oral presentation at the 1988 AGU Fall Meeting, San Francisco, Calif. *EOS (Trans. Am. Geophys. Union) 69*, 1078.

—, and —, 1989: Vertical distributions of particulate chlorine, nitrate, bromine, and combustion products in spring Arctic. Abstract of poster presentation at the 1989 AGU Fall Meeting, San Francisco, Calif., 4-8 December. *EOS (Trans. Am. Geophys. Union) 70*, 1018.

LORENZ, E.N., 1990: Effects of analysis and model errors on routine weather forecasts. In Seminar Proc. *Ten Years of Medium-Range Weather Forecasting Seminar Proceedings*, 4-8 September, 1989, European Center for Medium Range Weather Forecasting, Reading, U.K.

PRICE, M.F., 1990: The development of legislation and policies for Colorado's National Forests. *ETH-Zurich Forstwissenschaftliche Beitraege 10*, 281-299.

— , 1990: Global environmental change and the social sciences: evolution in progress? *EarthQuest 4*, 9, 12-13, 16.

— , 1990: Mountain forests as common-property resources: management policies and their outcomes in the Colorado Rockies and the Swiss Alps. *ETH-Zurich Forstwissenschaftliche Beitraege 9.*

*RILEY, J.J., M.P. LELONG, AND *D.N. SLINN, 1990: Organized structures in strongly-stratified flows. In *Turbulence and Coherent Structures*, (O. Métais and M. Lesieur, Eds.), Kluwer Academic Publishers, The Netherlands.

TILLEY, J.S., 1990: *On the Application of Edge Wave Theory to Terrain-bounded Cold Surges: A Numerical Study.* Cooperative Thesis NCAR/CT-130, NCAR, Boulder, Colo., 354 pp.

TURNIPSEED, A.A., 1990: *Kinetics of the Reactions of BrO Radicals with C10 and BrO, and the Chemiluminescent Reactions of Fluorine with Dimethyl Sulfide.* Cooperative Thesis NCAR/CT-127, NCAR, Boulder, Colo., 139 pp.

TWOHY, C.H., *B.J. HUEBERT, *P.A. DURKEE, and *R.J. CHARLSON, 1990: Airborne measurements of droplet chemistry in stratiform clouds. In

Preprint Vol. *AMS Conference on Cloud Physics*, San Francisco, CA, 23-27 June, 1990, 527-530.

UPCHURCH, G.R., Jr., and *R.A. ASKIN, 1990: Latest Cretaceous and earliest Tertiary dispersed plant cuticles from Seymour Island, Antarctica. *Antarctic J. U.S. 24(5)*, 7-10.

WINCHESTER, J.W., and S.-M. LI, 1988: Arctic megahaze aerosol tracer: Sulfur with silicon, but no aluminum! Long range transport of coal smoke? Abstract of oral presentation at the 1988 AGU Fall Meeting, San Francisco, Calif. *EOS (Trans. Am. Geophys. Union) 69*, 1078.

—— , and —— , 1989: Identifying biologically important aerosol components by statistical analysis of PIXE data. Abstract of paper for presentation at the *International Conference on Nuclear Analytical Methods in the Life Sciences*, Gaithersburg, MD, 17-21 April, 1989.

——, and ——, 1989: Marine aerosols, a mixture of components of importance to climate – a case study of the Arctic ocean atmosphere at Barrow, Alaska, U.S.A. Paper for presentation at *USSR-USA Symposium on Aerosols and Climate*, Obninsk, Russia, 28 August - 1 September, 1989.

—— , and —— , 1989: Trace element signature of coal smoke aerosol in the late winter Arctic atmosphere. Abstract of paper for presentation at *Annual Meeting of the American Association for Aerosol Research*, session on Aerosol Formation and Transport in Rural and Remote Areas, Reno, Nevada, 10-13 October, 1989.

* An asterisk denotes a non-NCAR author.

Previous PART0002