ronmental Research Laboratories
grams and Plans

FY 1986 Programs and FY 1987 Plans

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

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Environmental Research Laboratories
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Environmental Research Laboratories

The mission of the Environmental Research Laboratories (ERL) is to conduct an integrated program of fundamental research, related technology development, and services to improve understanding and prediction of the geophysical environment comprising the oceans and inland waters, the lower and upper atmosphere, the space environment, and the Earth.

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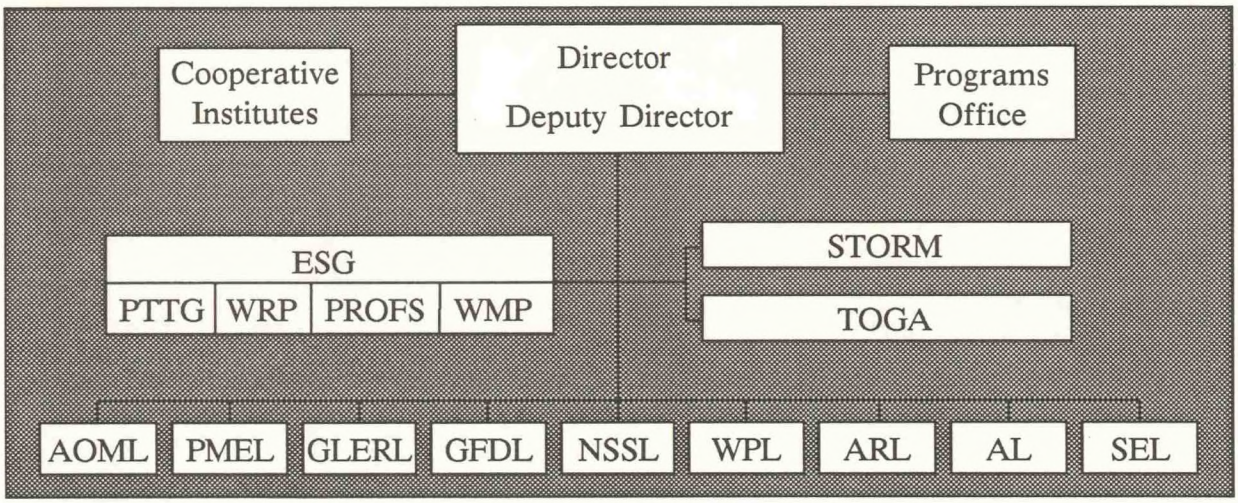
These are highlights of Laboratory accomplishments and abbreviated summaries of immediate objectives. More comprehensive and detailed descriptions of activities, results, and plans may be found in the Laboratories' annual reports (which may be obtained directly from the Laboratories) and in the open literature. Interested readers are referred to the annual *Environmental Research Laboratories Publication Abstracts*.



ENVIRONMENTAL RESEARCH LABORATORIES

The Environmental Research Laboratories (ERL) are organized within NOAA's Office of Oceanic and Atmospheric Research and have their headquarters in Boulder, Colorado. They include major units located throughout the United States:

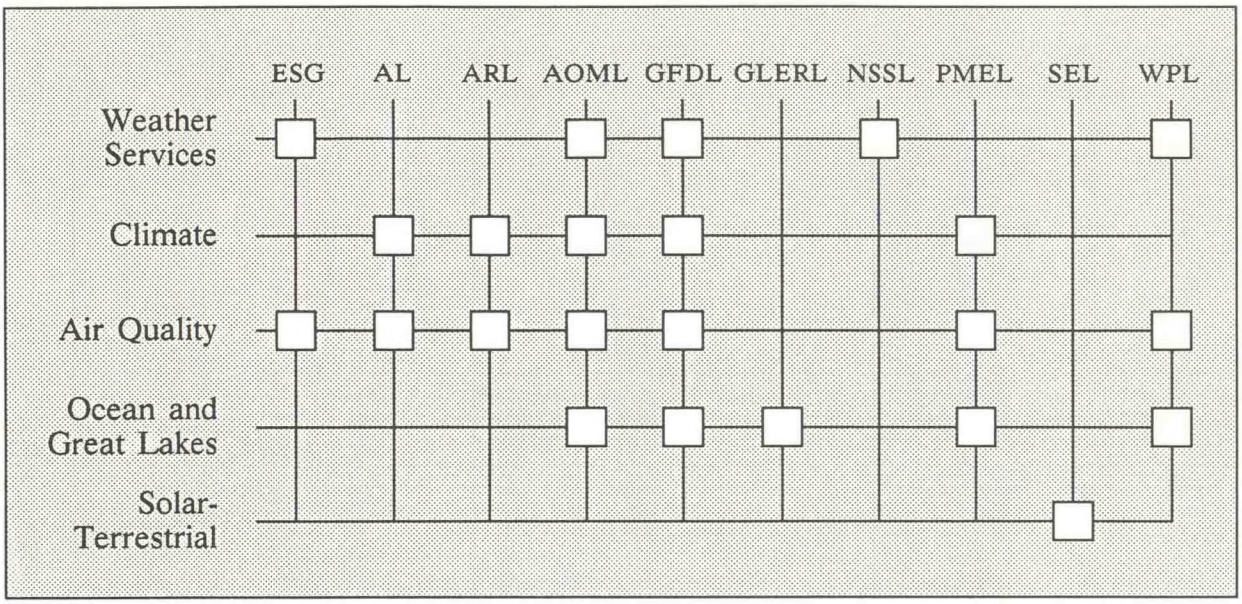
Aeronomy Laboratory (AL)	Boulder, Colorado
Atlantic Oceanographic and Meteorological Laboratory (AOML)	Miami, Florida
Air Resources Laboratory (ARL)	Silver Spring, Maryland
Environmental Sciences Group (ESG)	Boulder, Colorado
Geophysical Fluid Dynamics Laboratory (GFDL)	Princeton, New Jersey
Great Lakes Environmental Research Laboratory (GLERL)	Ann Arbor, Michigan
National Severe Storms Laboratory (NSSL)	Norman, Oklahoma
Pacific Marine Environmental Laboratory (PMEL)	Seattle, Washington
Space Environment Laboratory (SEL)	Boulder, Colorado
Wave Propagation Laboratory (WPL)	Boulder, Colorado

In addition, institutes administered jointly by ERL and universities undertake research for ERL. ERL also sponsors research through contracts and grants to universities, State and Federal agencies, and private enterprise. Many ERL research efforts rely on the cooperation of other NOAA elements, including NESDIS, NOS, NMFS, and the Office of Aircraft Operations.

ERL's program includes fundamental research to develop technology and improve NOAA services to the public. Samples of research results are Doppler radar technology (to improve tornado detection and warnings), mathematical models (to predict climate and ocean variations and to improve hurricane forecasting), ocean current forecasts (to minimize ship operation costs), observations of ocean upwelling (to maximize fish catches), and solar activity forecasts (to protect astronauts, for example).

Users of ERL research results include the atmospheric, marine, and space research communities, NOAA service components (NWS, NOS, NESDIS), Federal, State, and local governments, and the private sector.

The ERL program is broad, embracing studies relating to the oceans and Great Lakes, the lower and upper atmosphere, and the solar-terrestrial environment. Studies and activities focus in five subject areas: Weather Observation and Prediction, Climate, Air Quality, Ocean and Great Lakes, and Solar-Terrestrial Research and Services.



The following summary of ERL research is organized in terms of subject areas. Succeeding sections discuss the accomplishments and plans of the individual Laboratories and other units. The Appendix lists acronyms and initialisms used in those sections.

WEATHER OBSERVATION AND PREDICTION

Weather observation and prediction studies and activities include programs of AL, AOML, GFDL, NSSL, ESG (WRP, PROFS, WMP and until FY 1987, CRP), WPL, and the joint institutes. These programs interact directly with Ocean and Great Lakes Prediction R&D and with Solar-Terrestrial Research and Services programs dealing with the lower and upper physical boundaries of the atmosphere, with Air Quality programs relating to the short term, and with Climate programs relating to the long term. Weather programs include research on observational systems, modeling and prediction, severe storms, hurricanes, sea-air interaction, cloud and precipitation processes, mesoscale meteorology, and synoptic weather, and technology transfer.

Observational Systems

The Boulder Atmospheric Observatory (BAO) includes a 300-m-high meteorological tower and associated remote sensors. The atmospheric research conducted at this facility includes micrometeorological and boundary layer studies, and meso-beta-scale (i.e., scales up to 200 km) research. The latter research includes downslope wind situations and studies of clouds and precipitation under upslope conditions. Smaller scale research concerns low-level winds, microbursts, and wind shear, important to aircraft operations.

The most versatile and successful observational tools are radar and lidar. Techniques being developed using radar remote sensing include optical and infrared scintillation for measurement of wind

(path-averaged values), refractivity fluctuations, heat and moisture flux, rainfall rate, and drop size distribution. Doppler radar research continues on flow and precipitation fields within severe thunderstorms, to support the interagency NEXRAD Program, whose goal is to produce a national Doppler radar network by the late 1980s. Also in development are optical and infrared lidar techniques for the remote measurement of winds, temperature, humidity, and aerosols; passive microwave techniques for the measurement of temperature and humidity profiles and cloud liquid; and active radar techniques for the measurement of winds, clouds, precipitation, turbulence, and refractivity fluctuations. As techniques are developed and verified, they are transferred to operational NOAA programs, or to the wider scientific community.

Vertically pointing radars at Platteville, Stapleton International Airport in Denver, and three other sites in Colorado provide real-time wind speed and direction profiles. They are research prototypes of a Profiler system being developed to supplement radiosonde wind-measuring capability. Microwave radiometer devices for vertically sensing water vapor, liquid water, and temperature are also part of this Colorado network. They too are research prototypes for the Profiler system, intended to supplement radiosonde capabilities.

Modeling and Prediction

ERL modeling and prediction efforts meet several goals. In the large scale, goals are to develop or improve atmospheric prediction models in the one-half to 30-day time frame, to identify external forcing mechanisms that models must include to simulate the evolution of macroscale atmospheric disturbances over the range of several weeks to 4 months, and to search for a physically based, probabilistic approach for long-range simulation of atmospheric variations. In the mesoscale, goals include understanding of hurricane dynamics, including the study of small-scale features within hurricane systems; and production of accurate numerical simulations of mesoscale processes, to understand the role of scale interactions in severe-storm generation and evolution. The ultimate goal is to improve operational forecasting through better understanding and improved model guidance.

Severe Storms

Severe-storm researchers acquire data with specially developed instruments, and analyze these and conventionally acquired data to obtain a more comprehensive understanding of severe storms, to develop models of convective storms, to compare models with observations, and ultimately to improve prediction of severe storms.

Instrumentation developed in ERL for this research includes automatic surface networks, an instrumented television tower, the BAO, two large 10-cm Doppler radars, an atmospheric electricity measurement system, two 3-cm transportable Doppler radars, and an infrared Doppler lidar to measure three-dimensional velocity fields in and near convective storms, and pressure sensor arrays to detect and monitor gust fronts and microbursts in the vicinity of airports. Increasing use is being made of interactive data processing and display technology to study data in the severe storm environment.

Hurricanes

Hurricane research involves three major activities: Hurricane field research, hurricane modeling, and hurricane prediction research.

- Hurricane field research assembles the descriptive data needed to support analytical and theoretical studies to improve the understanding of hurricane structure and behavior. The ultimate purpose is to improve operational NWS forecasting of hurricanes. The field pro-

gram uses air- and ground-based radar, aircraft, and satellite observations. Uniquely equipped NOAA P–3 aircraft fly approximately 100 hurricane research hours per year. Investigations include boundary layer processes, evolution of convection and associated wind fields, hurricane motion and internal dynamics, cloud microphysics, and flow characteristics in and near the eyewall and adjacent spiral rainbands.

- Hurricane modeling research seeks to develop and improve models for use in operational hurricane intensity and track forecasting.

- Hurricane prediction research involves a combination of efforts to study pre-hurricane disturbances, hurricane genesis and development, hurricane climatology, general tropical meteorology, radar precipitation measurement, analysis of Seasat satellite data, and hurricane sea-air exchange processes.

Air-Sea Interaction

Air-sea interaction research involves the experimental study and numerical modeling of air-sea interactions, especially under extreme weather conditions such as hurricanes. Experimental studies rely on aircraft observations of air-sea (or air-lake) interactions, such as surface wind and wave fields under a wide range of conditions. These observations are compared with model predictions of waves and storm surges, to test hypotheses and understandings, and to validate or improve the models.

Cloud and Precipitation Processes

Research on cloud and precipitation processes involves numerical modeling of convective clouds to predict precipitation and phenomena such as downbursts that are hazards to aviation. To support these experiments, optical, infrared, and microwave radar and lidar systems are used to measure cloud-echo intensities as a function of three-dimensional space and time. These echo-intensity fields can be measured as a function of both wavelength and polarization. The Doppler effect is used at radio and optical and infrared frequencies to determine velocity fields and turbulent kinetic energy dissipation rates. The multifrequency approach provides information on droplet size, and dual polarization permits identification of the cloud or precipitation particles as spherical water droplets or nonspherical ice crystals. Microwave radiometric techniques are used to measure line integrals of cloud liquid water and water vapor.

Precipitation Chemistry, Cloud Physics, and Technology Development

NOAA conducts cloud physics research on hurricanes and related convective cloud systems. In field programs, research aircraft penetrate hurricane circulations to gather data on structural characteristics, ranging from cloud microphysical to digital radar data. The observational efforts contribute to the development of numerical models of hurricanes.

A Federal-State Cooperative Program develops criteria for the effective evaluation of operational cloud seeding. The research and development needed to establish these criteria are carried out through contracts to four States under a Congressional mandate. NOAA manages the contracts and coordinates the research.

The program provides cost-effective research opportunities to develop technologies that address goals in agriculture, energy, and water resources. Current activities include studies on midwestern

summer rainfall enhancement for corn and soybean production, by Illinois; the importance of western seed ing programs to water supplies in downwind acid-rain regions, by Nevada; the physics of hail-storms and the enhancement of rain over the Great Plains, by North Dakota; and the enhancement of intermountain snowfall for irrigation and energy uses, by Utah.

Mesoscale Processes

Mesoscale research includes the study of atmospheric processes, with particular emphasis on meso-alpha-scale convective systems. This includes work to improve understanding of the conditions producing excessive convective rainfall and to develop techniques for forecasting flash-flood-producing storms. Other activities are development of mesoscale numerical models, conduct of theoretical and diagnostic studies, analyses of mesoscale weather systems, and study of the microstructure and turbulence of the atmospheric boundary layer using airborne and remote-sensing measurement techniques.

Technology Transfer

ERL develops, tests, and verifies operational sensing systems for transfer to service components of NOAA such as NWS, and to other Federal agencies such as the Federal Aviation Administration (FAA). Doppler radar for identifying and warning of severe thunderstorms and tornadoes has been tested for NWS, the Air Force, and the FAA. These tests indicate that Doppler radar can reliably detect destructive tornadoes many minutes before they produce damage.

ERL, NWS, and NESDIS cooperate to improve local weather information service systems for NWS. System designs incorporate many advances of the past decade in satellite- and ground-based remote sensing, in automated and surface weather stations, in data processing and display, in mesoscale analysis and forecasting, and in dissemination of data and forecasts.

CLIMATE

Climate studies involve eight Laboratories and four joint institutes. Climate programs interact directly with other major programs such as Air Quality, Solar-Terrestrial Research and Services, and Ocean and Great Lakes Predictions, and on shorter time scales, with Weather Observation and Prediction. Climate programs include ocean-atmosphere studies; observation and analysis of solar, atmospheric, and stratospheric variability; and climate modeling.

Ocean-Atmosphere Studies

A major ocean-atmosphere program, Equatorial Pacific Ocean Climate Studies (EPOCS), is investigating the physics and dynamics of the coupled ocean-atmosphere system in the equatorial Pacific as part of the international Tropical Oceans and Global Atmosphere (TOGA) program. Understanding this system is vital to comprehending global fluctuations of climate on interannual time scales. A broad spectrum of oceanographic and atmospheric parameters is being monitored by a variety of sensors to create an integrated data base. Satellites are continuously monitoring winds and sea-surface temperatures. Doppler radars are continuously monitoring wind profiles. Research vessels are using XBTs and current profilers to determine vertical thermal and dynamic cross sections. Moored arrays at or near the Equator are used to determine the major time scales of variability of ocean parameters such as current, temperature, and salinity. Drifting buoys are used in the Pacific equatorial current system to determine the larger scale current patterns as well as sea- surface temperature. Other projects are using aircraft to measure vertical fluxes of heat, moisture, and momentum over the tropical Pacific, and remote wind Profilers to develop an equatorial Pacific wind climatology.

Another major program, Subtropical Atlantic Climate Studies (STACS), seeks to identify the processes that contribute most to the poleward transport of heat in the North Atlantic Ocean and to develop the technology to monitor these processes operationally. The initial emphasis of STACS has been on developing techniques to monitor the mass transport and heat content of the Florida Current. Several techniques were tested to determine the most efficient approach for long-term monitoring of the Florida Current. The most effective and efficient were found to be measurement of electromagnetic induction from communications cables, and use of coastal tidal stations. Using these techniques, the STACS program began studying the currents entering the Caribbean Sea and the currents east of the Bahama Islands.

In addition to EPOCS and STACS, research is conducted on the temporal and spatial variability of water mass structure, sea level, currents, and general circulation of deep ocean and coastal waters. Vertical mixing processes in the upper-ocean, wind-generated response of middle-latitude upper ocean currents and temperature fields, methods of inferring surface wind stress fields from satellite data, and chemical exchanges with the atmosphere are specific concerns.

In a technology development project, the potential of using low-frequency sound sources and detectors (acoustic tomography) to measure the structure of the ocean is being investigated.

Climate Variability

Projects relating to climate variability include airborne measurement of solar radiation over the equatorial Pacific; recently completed construction of a global data set describing climate variations over the past 150 years; determination of the intensity and time scales of variations in solar ultraviolet radiation as a function of wavelength in the 110- to 400-nm range; and determination of the significance of such variations in molecular dissociation atmospheric chemistry, upper atmosphere heating, and measurements of atmospheric constituents. Global levels of atmospheric trace constituents that have significant effect on the Earth's radiation budget, including carbon dioxide, ozone, aerosols, water vapor, methane, halocarbons, and nitrous oxides are monitored and analyzed. Four monitoring stations (Alaska, Hawaii, Samoa, and South Pole)—one tropical and one high-latitude in each hemisphere—provide baseline observations for monitoring global air quality. These stations are supplemented by several specialized monitoring networks operated by groups from the United States and other nations. These monitoring stations, which perform measurements for research related to climate change, are supported by instrument calibration and development in ERL. Analysis and interpretation of the data from the stations focus on air quality changes that might affect climate, with special emphasis on carbon dioxide. ERL conducts additional reimbursable research involving the measurements of solar radiation, temperature, and other parameters above a forest canopy to improve understanding of the biosphere as a component of the climate system.

Ongoing chemical modeling includes analyses of atmospheric nitrous oxide, reactive nitrogen (natural plus anthropogenic), and ozone. Models are being developed to include a number of trace constituents simultaneously. This capability will be used to run interdependent experiments involving ozone and its precursors, partitioned components of total reactive nitrogen, and carbon monoxide.

Climate Modeling

Mathematical models of the atmosphere, the oceans, and the coupled fluid system are constructed to simulate the large-scale features of climate variability. The atmospheric studies have three emphases:

- Description of the dynamical interaction between large-scale wave disturbances and the general circulation of the atmosphere.

- Identification of the physical and dynamical mechanisms that maintain climate and cause its variation.
- Evaluation of the effects of human activities on climate.

Ocean circulation studies, also central to climate research, concern the following:

- The large-scale response of the ocean to atmospheric forcing over a range of time scales from weeks to decades.
- Ocean observational studies of the density structure and fields of various tracers, development of models of the world's oceans.
- Interpretation of results in terms of a coherent hydrodynamical and thermodynamical framework.
- Development of a capability to predict the large-scale behavior of the world's oceans in response to changing atmospheric conditions.

The aim of ERL climate observational studies is to identify and evaluate the physical processes by which atmospheric and oceanic circulations are maintained and to compare observational results with diagnostic studies of atmospheric and oceanic models.

Radiatively Important Trace Species

In FY 1985, NOAA began a new research program, Radiatively Important Trace Species (RITS): Trends and Mechanisms, that focuses on a unique set of trace species in the atmosphere. This set is composed of those constituents that are both radiatively and chemically active. The environmental issues that these species pose are twofold. First, it has become clear that carbon dioxide (CO_2) is not the only "greenhouse" species. There are others, such as chlorofluorocarbons (CFCs), methane, ozone (in the lower atmosphere), nitrous oxide, and water vapor (in the stratosphere). If these increases continue, it is estimated that the global "greenhouse" warming from these gases will be as great as, and additive to, that expected from the CO_2 increases. Second, these species, unlike CO_2, are chemically reactive with other species in the atmosphere. Indeed, many of these species are the principal actors in atmospheric chemistry.

NOAA has recognized that the reasons for the increasing abundances of these non-CO_2 "greenhouse" gases must be understood and that the potential climatic and chemical consequences of such changes must be predicted reliably. The RITS program was initiated to provide this understanding. NOAA was the first to justify this need, and the RITS program is the only coordinated start on this important scientific challenge and environmental problem.

The RITS program has four major research activities:

- Long-term monitoring to determine the temporal trends of the radiatively active trace species.
- Chemical studies to understand the key reactions that form and remove these species.
- Global transport and source sink investigations to determine how the species are distributed throughout the atmosphere and how they are emitted from or lost to surface areas.
- Model development to assimilate the source, sink, chemical, and transport information into a theoretical framework that can explain the observed RITS trends and distributions and

predict possible future climatic and chemical effects from natural or human-induced changes in the abundances of the radiatively and chemically important trace species.

AIR QUALITY

Air quality research determines sources, transport and dispersion, and fates of trace constituents and pollutants, to enable government and industry to reduce adverse impacts and maintain the chemical health of the atmosphere.

Air quality has a great effect on human health and ecology, and possible short-term and long-term effects on global weather and climate. NOAA has the responsibility to develop measurement techniques for important atmospheric constituents, to measure the spatial and temporal distribution of the constituents, to measure cross sections for the interactions involving and affecting important atmospheric constituents, and to perform modeling studies to understand the physics and chemistry of the atmosphere and the long-term effects of human-induced changes. NOAA carries out the tasks of ascertaining the sources of pollutants in nature and in human activities. It explores the fate of atmospheric constituents such as aerosols, particulates, and gases, and assesses the geophysical consequences of energy production. This research provides the scientific basis for regulating industrial, agricultural, and other polluting but economically necessary activities.

The Aeronomy Laboratory (AL) conducts research on chemical and physical processes of the Earth's atmosphere to advance the capability of monitoring, predicting, and controlling the quality of the atmosphere. Research methods involve both in situ and remote measurement of critical atmospheric parameters, including chemical composition and dynamic properties, such as wind velocities, turbulence, and wave motions. Theoretical programs in atmospheric photochemical modeling and in atmospheric dynamics and transport support the observation programs. An experimental laboratory chemical kinetics program supports the theoretical photochemical modeling program and also supplies input for the development of new atmospheric monitoring and measurement technology.

The Air Resources Laboratory (ARL) operates baseline stations for measuring atmospheric constituents important in air quality variation (see also Climate Research); conducts field and laboratory investigations into the physics and chemistry of formation of natural and anthropogenic particles and gases, the dispersion, transformation, and sinks of these particles, and the scavenging of particles and gases by clouds; and develops and disseminates air quality simulation models for inert and reactive pollutants on all temporal and spatial scales.

The Wave Propagation Laboratory (WPL) and the Geophysical Fluid Dynamics Laboratory (GFDL) contribute remote-sensing measurement and atmospheric circulation and chemical modeling capabilities, respectively, to aid in solution of the air quality problems of transport and transformation. Currently the focuses of their air quality programs are Ozone, Acid Rain, Transport and Diffusion, and Modeling. There is close association with the program of Geophysical Monitoring for Climatic Change (GMCC; see Climate Research) and the programs of Weather- and Marine Observation and Prediction.

The Atlantic Oceanographic and Meteorological Laboratory (AOML) and Pacific Marine Environmental Laboratory (PMEL) conduct research on the natural marine sources of tracer constituents and pollutants.

Ozone

In recent years, the chemistry of the stratosphere has been of great interest because of the recognition of human potential for inadvertently depleting the stratospheric ozone layer, with disastrous consequences. First, the possibility of an ozone reduction from water and nitrogen oxides released in stratospheric flights of supersonic transports was considered. This problem brought worldwide attention

to the potential for global air pollution problems. More recently, chlorine-containing halocarbons have been labeled potential threats to stratospheric ozone. In addition to the effects on biological systems, ozone loss may also precipitate climatic changes.

The monitoring program calibrates ozone measurement devices used at three ERL sites and other worldwide ozone-monitoring sites. Measurements and studies of transport and chemistry affecting ozone are being conducted. One radical important in ozone chemistry is NO_3, formed when nitrogen dioxide reacts with ozone. Research is improving our understanding of the chemistry of NO_3, required for interpreting the role of nitrogen oxides in the stratosphere and troposphere.

There is still considerable uncertainty about pathways of pollutants to the stratosphere, where ozone is important to ultraviolet absorption of solar radiation. Towering cumulus clouds in the western Pacific are a source of stratospheric water vapor, and hence a potential path for pollutants to enter the stratosphere and interact with the ozone. Further quantitative measurements are in progress.

Laser magnetic resonance and laser-induced fluorescence techniques are used to measure important reaction rates and cross sections. The fluorescence technique is being used to measure various NO_3 reaction parameters and kinetics.

Acid Rain

The principal issues in the Acid Rain program are (1) the gradual acidification of surface waters and soils by acid rain and dry deposition, and (2) the transboundary (especially U.S.-Canada) transport of acidifying pollutants. NOAA is an agency in the National Acid Precipitation Assessment Program (NAPAP) and has the principal research responsibility in three areas:

- Assessing natural sources or causes of acidity and their importance relative to human-activity sources, to facilitate control strategies.

- Defining and assessing atmospheric processes of transport, dispersion, and transformation that link emissions of pollutants with acid deposition.

- Interpreting deposition mechanisms that bring acidic pollutants to the Earth's surface, and assessing the consequent severity and extent of the acid deposition phenomenon.

A network of monitoring sites is being established to determine the quantity and type of acid material that is being deposited in North America. One remote site is at the 10,000-ft level on Niwot Ridge, in Colorado. Depending on wind condition, the site can be used to examine the "clean air" from the west and the relatively polluted air from the Denver metropolitan area to the east. The site is being used to test current understanding of the photochemistry whereby NO_3 is formed from NO and NO2. Other studies permit estimates of the seasonal dependences of the dry removal rates of HNO_3, which appear to be much faster in summer than winter.

Natural sources of acid rain precursors have been found in the Gulf and the North Pacific Oceans. Research on these natural sources includes water and atmospheric sampling for volatile sulfur species to assess exchange rates and source/sink relationships for these gases, sulfur metabolism studies at sea using radio-sulfur and natural phytoplankton populations, and studies of the influence of ocean-emitted gases on the acidity of marine-derived precipitation. It has been found that the major marine source with potential significance to the United States is the Pacific Ocean. Pre-acidic material, transported across coastal boundaries, is also being measured.

The Environmental Sciences Group conducts cooperative sampling and analysis studies with universities, other agencies, and institutions. Recent emphasis has been in the Gulf of Mexico where gas and aerosol samples, as well as precipitation samples, were collected on a joint ERL - Mexico oceanographic research cruise.

Transport and Diffusion

The problem of transport and diffusion is important to a larger class of air quality programs. NOAA research in this area includes field programs, analysis, and modeling. Major field programs being analyzed or completed are the Cross-Appalachian Tracer Experiments (CAPTEX 1982 and 1983), the Atlantic Coastal Unique Regional Atmospheric Tracer Experiment (ACURATE), and the Metropolitan Tracer Experiment (METREX). These are multi-agency experiments and include several Laboratories. Results are used to develop and verify models to determine the effect of surface roughness and complex mountainous terrain on the measurement of air trajectories, and the effects of atmospheric anomalies (i.e., inversions) on transport and diffusion.

Modeling

The main goal of ERL modeling research is to understand the formation, transport, and chemistry of atmospheric trace constituents. Such understanding requires judicious combinations of theoretical models andz specialized observations. The understanding gained will be applied toward evaluating the sensitivity of the atmospheric chemical system to human activities. Ongoing chemical modeling at GFDL includes analyses of atmospheric nitrous oxide, reactive nitrogen (natural plus anthropogenic), and ozone. Models are being developed to include a number of trace constituents simultaneously. This capability will be used to run interdependent experiments involving ozone and its precursors, partitioned components of total reactive nitrogen, and carbon monoxide.

Transport models are being developed to simulate and/or predict local, regional, and global transport and diffusion of pollutants injected into the atmosphere. The models are used to evaluate the environmental effects of various kinds of energy production (e.g., nuclear fuels or fossil fuels) and of volcanic eruptions, and to predict the path of radioactive debris from atmospheric nuclear tests. In the acid rain program, a major goal is to establish the source-receptor relationships between sulfur emissions and acid deposition.

OCEAN AND GREAT LAKES PREDICTION

The ocean and lake observation and prediction program is accomplished at AOML, GFDL, GLERL, PMEL, WPL, and joint institutes. The program interacts strongly with the Climate, Air Quality, and other marine programs. This research improves the capability for providing services to the marine community through increased understanding and improved observations of the behavior of the atmospheric boundary layer over the ocean, the wave and current motions in surface layers, and the physical properties of the surface and subsurface waters of the ocean.

Winds and Waves

ERL conducts research to improve the observation and forecasting of hazardous winds and waves that affect homeowners, recreational boaters, the oil and gas industry, fishing, and commercial transportation. Surface winds provide the driving force for the generation of other phenomena such as waves, currents, upwelling, and storm surges. Until wind stress, which provides the major driving force, can be measured directly, it must be computed from the wind field in the boundary layer immediately above the water surface. Since winds measured at coastal weather stations are often not representative, increased emphasis is being placed on developing in situ and remote-sensing techniques for directly measuring over-the-water winds.

In addition to improving the models used for wave predictions and improving the understanding of wave dynamics, ERL is developing and applying new techniques such as ground-based radar, airborne

imaging radar, airborne laser wave profilometry, and satellite observations to observe the sea state or parameters for predicting sea state.

Hurricanes and other violent storms often cause surges of water that can be 15–20 ft above the normal water level. These surges become especially dangerous when combined with a high tide or high-wave conditions. Present techniques for forecasting the timing, extent of coastline affected, and magnitude of the inundation are inadequate to ensure the safety of coastal populations. Research to address these deficiencies includes the topographically complex areas of bays and inlets, complicating factors such as inhomogeneities in the wind field, variations in water depth offshore, and the effects of waves and currents.

Tsunamis

Earthquake-induced ocean waves (tsunamis) can travel great distances at high speeds and can cause extensive damage to coastal communities. A goal of ERL tsunami research is improved prediction and monitoring of these waves. Such improvements require the capability to determine in real time the expected tsunami height and runup at various coastal locations. Qualitative forecasts based on historical data are now possible, but quantitative forecasts are not. Key areas of research include tsunami generation, open-ocean propagation, numerical modeling, and instrument development to monitor micro-tsunamis for analytical and numerical models and to detect tsunamis before landfall for operational warnings. Information obtained is being incorporated into an operational warning system to provide reliable (low false-alarm rate) and accurate warnings.

Ice

Ice research in ERL seeks to improve monitoring and prediction of growth, movement, and breakup of ice in the Bering Sea, along the Alaskan Arctic coast, and in the Great Lakes. In the Great Lakes, accurate forecasts of ice thickness and extent in near-shore areas and connecting channels would allow extension of the commercial navigation season and improved design of nuclear reactor coolant intakes. Ice formation and growth occur by in-place thermal growth or movement of ice from other areas by wind and waves. Thermodynamic models of ice cover indicate that optical properties of ice are extremely critical to accurate forecasts of ice cover. Hence, a knowledge of light transmission, absorption, and reflection characteristics of the many ice types common to the Great Lakes is essential for modeling, remote sensing, and energy budget studies. Regional models for ice forecasts are being developed and transferred to the National Weather Service for operational use. These models incorporate ice and wind dynamics and ice thermodynamics as well as local coastal geometries and site-specific user requirements.

OCEAN AND GREAT LAKES ASSESSMENT

Marine assessment includes contributions from AOML, GFDL, GLERL, PMEL, and joint institutes. ERL conducts process-oriented research to improve our understanding of natural oceanic and Great Lakes systems and the ecological impacts of human-induced stresses on these systems; problem-oriented research leads to improved assessment capabilities. ERL develops and transfers scientific information to support decisions pertinent to marine pollution, exploitation of living and nonliving marine resources, water utilization, coastal power generation, and other activities affecting marine ecosystems. Research focuses on coastal regions, estuaries, and the Great Lakes and concerns a variety of topics:

- Dynamics and kinematics of water circulation.

- Transport, transformation, and fate of pollutants, and effects of pollutants on marine ecosystems.
- Ecosystem and nutrient dynamics.
- The effects of physical and biochemical processes on marine productivity.
- Water supplies, lake levels, and flows in the Great Lakes system.
- Development and application of marine prediction models, risk analysis techniques, and advisory services.

Research on the effects of ocean use consists of field investigations and supportive laboratory research to determine the consequences of dumping dredged material and municipal and industrial wastes into marine waters. Emphases are on fates of pollutants and the development of techniques to measure pollutants. Research is conducted to detect changes in the oceans and the Great Lakes that are caused by human activities and that may have long-term adverse consequences. Research focuses on the interaction of trace metals, synthetic organics, and hydrocarbons with marine ecosystems. The role of particulates as pollutants or as a transport mechanism for harmful compounds is paramount.

Research conducted by PMEL describes and quantifies the physical and chemical processes affecting the transport, transformation, and fate of pollutants in marine estuaries and coastal systems. Studies focus on pollutant levels and distributions; chemical transformation of pollutants and uptake by particulates; pollutant source/sink distributions; and estuarine and coastal circulation patterns and mixing processes. The primary effort is in the Puget Sound System. PMEL also conducts research to develop models of mass fluxes of trace metals and toxic organics in coastal and estuarine systems. Research stresses the incorporation of information on pollutant loading and on physical and chemical processes obtained from field studies into dynamic models of water movements and pollutant distributions and fluxes. PMEL provides information on coastal and estuarine processes that affect the ability of marine systems to accommodate contaminants without unacceptable damage. This information synthesizes the results of field studies and models to determine relationships useful for decision-making purposes, among pollutant types, distribution and levels of loading, pollutant transport and dissipative processes, and ecological consequences.

At GFDL, research related to the quality of the marine environment has as its objective the simulation of conditions in coastal zones and in estuaries, and the modeling of the dispersion of geochemical tracers (e.g., tritium, radon) in the world oceans. Two- and three-dimensional models of estuaries such as the Hudson-Raritan and Delaware Estuaries have been developed. The response of coastal zones to transient atmospheric storms, and the nature of upwelling processes (which are of great importance to fisheries), are being studied with a variety of models.

GLERL conducts research in the Great Lakes on water movement and temperature, particle dynamics, cycling of toxic organics, planktonic succession, eutrophication and nutrient cycling, and the development of environmental in formation services and environmental engineering models and applications. The water movement and temperature research develops improved climatological in formation (by means of observations, new instrumentation, and improved analysis) on the distribution and variability of coastal and offshore currents and develops and tests improved numerical hydrodynamic models that can simulate and predict lake currents and temperatures, and extends models to simulate and predict the transport and diffusion of pollutants. Research in the Great Lakes also emphasizes the interaction of particulates and pollutants, particularly the pollutant source/sink characteristics of bottom sediments. GLERL also develops ecosystem models that simulate the passage of toxic pollutants through the Great Lakes food chain.

A major effort at GLERL develops, tests, evaluates, and applies water quality and water quantity management models and improved environmental systems engineering methods to estimate pollutant and nutrient loading; to estimate effects of diversions, consumptive use, human-induced changes in

lake water levels, and levels and flows in the connecting channels; and to organize and disseminate environmental information for decision purposes.

MARINE RESOURCES ASSESSMENT

Marine resources research is accomplished through projects at AOML, GLERL, PMEL, and joint institutes. The program is designed to accelerate rational marine industrial development through research into the optimum use, development, and protection of living and mineral marine resources; to improve, through applied research, the technologies needed for efficient use of marine resources; and to provide significant information on the social, economic, and legal impacts of present and projected marine development.

Submarine Hydrothermal Venting Systems

ERL increased its research on submarine hydrothermal venting systems at seafloor-spreading centers in response to the growing recognition of the environmental importance of the hydrothermal fluids. Factors such as possible economic importance of mineralized deposits have generated much of the recent interest in processes at seafloor-spreading centers. However, the basic lack of understanding of the environmental role of the hydrothermal fluids is the focus of ERL's research. Consequently, ERL's program is designed to assess the importance of hydrothermal fluids in altering the physical, chemical, biological, and geological characteristics of the marine environment into which the fluids are introduced.

Fisheries Oceanography

ERL conducts research on living marine resources in cooperation with NMFS. The goal of ERL is to develop an understanding of the direct and indirect effects of atmospheric and oceanic variations on fish and shellfish populations. The Fisheries Oceanography Coordinated Investigations (FOCI) program with NMFS emphasizes simultaneous interdisciplinary research aimed at understanding the variability of fisheries recruitment.

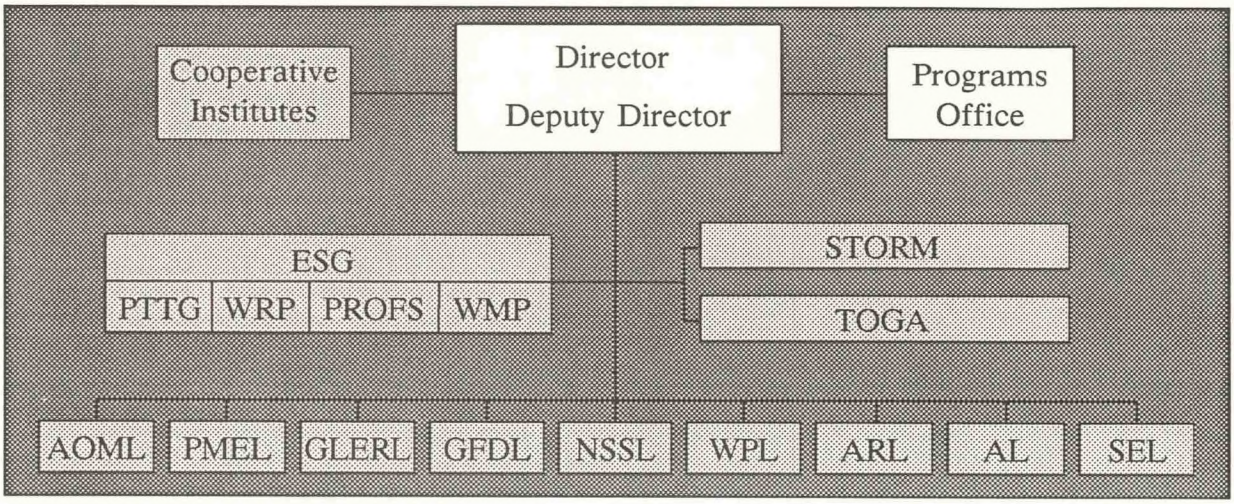
SOLAR TERRESTRIAL RESEARCH AND SERVICES

The solar-terrestrial program of SEL is unique in ERL because it contains both research and service components, and because the major user of the research component is the service component. The solar-terrestrial program interacts strongly with other government agencies, especially DOD and NASA. The goals of the program are to promote efficient, safe, and economic utilization of extraterrestrial space for civilian and military activities, vehicular operations, and communications; to support effective operation of essential public services that are subject to disruption by magnetic storms or solar events; and to increase understanding of the physical processes in the near-Earth space environment and their relation to human activities.

The program maintains continuous operation of the Space Environment Services Center (SESC) at Boulder, Colorado, for monitoring and predicting solar activity and events in the upper atmosphere, and for acquiring and processing data from space environment monitors on the Geostationary Operational Environmental Satellites (GOES) and the polar-orbiting TIROS–N and NOAA satellites. SESC, operated jointly with the U.S. Air Force Air Weather Service, is both the national and international center for operational space and upper atmosphere information. SESC provides forecasts and warnings of solar disturbances and their effects to government agencies, industries, universities, foreign govern-

ments, and other foreign and domestic users. These forecasts and warnings help to prevent failure of some aircraft and marine navigation and communications systems at high latitudes, and they help to improve the efficiency of all telecommunications systems, the effectiveness of military operations and solar-disturbance-sensitive research programs, and the reliability of electric power networks. Real-time observations of the Sun and space environment are the basis for forecasts and warnings.

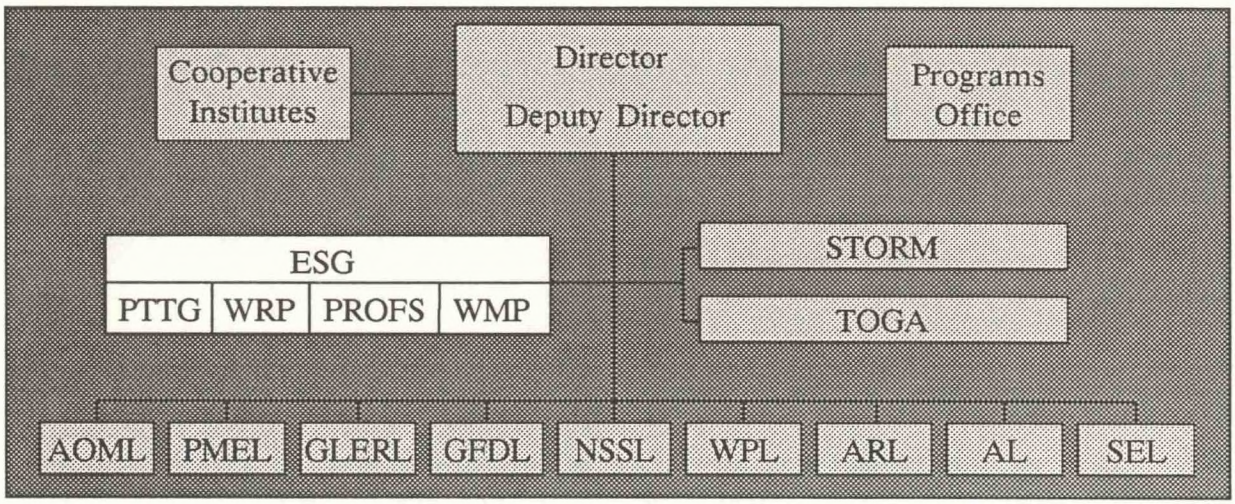
Research is undertaken to understand and model the fundamental physical processes responsible for the observed energy release, in the form of electromagnetic radiation and charged particles from the solar surface during solar disturbances; the propagation and modification of this energy through interplanetary space to the near-Earth environment; the transfer of this energy into the Earth's magnetic field; and the behavior and subsequent effects of this energy within the magnetosphere, the ionosphere, and the upper atmosphere. These studies use data from satellites, rocket-launched instruments, and ground stations. The ultimate goal of this research is to develop numerical models that can be used by SESC to predict, with increasing accuracy, the timing and geographic distribution of the effects of solar disturbances on the Earth's environment and on human activities.



OFFICE OF THE DIRECTOR
Boulder, Colorado
Vernon E. Derr, Director
Robert J. Mahler, Acting Deputy Director

The Director, assisted by the Deputy Director, establishes basic policies and manages the overall activities of the Environmental Research Laboratories. Within the Office of the Director, the Programs Office provides advice and services to the Director as well as to the Laboratories and ESG. The Programs Office provides advice and support in areas of policy, program planning, budgeting, and analysis; program coordination and review; and implementation of management decisions. Budget, ADP Planning and Telecommunications, and editing services are part of the Programs Office.

The National Research Council (NRC) of the National Academy of Sciences and NOAA conduct a Resident Research Associateship Program. Although a NOAA program, it is administered through the Office of the Director (ERL). The NOAA/NRC programs involve ERL, the National Weather Service, the National Environmental Satellite, Data, and Information Service, the National Ocean Service, and the National Marine Fisheries Service. NRC and NOAA conduct an annual international competition for about ten new awards per year to outstanding scientists and engineers at the recent-postdoctoral and experienced-senior levels; awardees receive 1-year appointments as guest investigators at participating NOAA Laboratories. There are approximately 175 active Research Advisors and more than 100 advertised research opportunities NOAA-wide.



ENVIRONMENTAL SCIENCES GROUP
Boulder, Colorado
William H. Hooke, Director

The Environmental Sciences Group (ESG) plans, conducts, and coordinates well-defined, high-priority programs of environmental research and technology development, which frequently require an intensive, concerted, or interlaboratory approach for success. Research findings and technological advances are actively transferred to other NOAA line organizations and the national user community.

Ongoing research and development activities are directed toward understanding precipitation, and convective weather processes; developing and evaluating advanced environmental monitoring, forecasting, and modification technologies; and building environmental data bases for use by the scientific community. ESG works with the cooperative institutes and other outside organizations to meet these responsibilities.

In FY 1986 ESG included the Program for Regional Observing and Forecasting Services, the Weather Research Program, the Weather Modification Program, and the Climate Research Program. WPL's Profiler Technology Transfer group became part of ESG at the beginning of FY 1987. This change reflects the maturity of wind Profiler development to the stage where it is nearing operational demonstration. Also at the beginning of FY 1987, the Climate Research Program transferred to the Air Resources Laboratory, reflecting the close association of climate research and global monitoring.

CLIMATE RESEARCH PROGRAM

CLIMATE RECORD CONSTRUCTION

Accomplishments FY 1986

Work continued toward Release 2 of the Comprehensive Ocean-Atmosphere Data Set (COADS). The Highly Reflective Cloud (HRC) data set continues to be updated on a near-real-time basis. More than 15 years of HRC data are now available. A descriptive climatology of the first 15 years of HRC

data was prepared for publication. Work comparing the HRC data set and the GOES Precipitation Index (GPI) at the University of St. Thomas in Houston indicates good correspondence between the two data sets.

A gridded set of monthly, seasonal, and annual precipitation anomalies has been compiled for Northern Hemisphere land areas using 1,487 individual station records. The record extends from 1851 (for parts of North America and Europe) through 1980.

A data set consisting of 5-day averages of 250-mb and 850-mb winds (1 November 1974 through 1 April 1986) and outgoing longwave radiation (1 June 1974 – 1 April 1986) was completed. Monthly and seasonal means and anomalies were calculated. This data set is continually updated on a real-time basis.

Plans FY 1987

Release 2 of COADS, to be completed in FY 1987, will extend all observational products and 2° latitude × 2° longitude monthly summaries through 1985. This constitutes the archival phase of a three-tiered update scheme that has been proposed in connection with real-time climate monitoring.

Between archival COADS updates, planned about every 5 years, annual data will be translated into Compressed Marine Reports (CMR). The mean and number of observations will be calculated for each of six variables: sea-surface temperature, air temperature, scalar wind, U and V components of the vector wind, and sea-level pressure.

Between annual COADS updates, global ship reports received monthly will be translated into CMR. A set of 2° monthly summaries, plus 4° latitude × 4° longitude composites will be produced for routine use in real-time monitoring.

Although the HRC data set will continue to be updated on a near-real-time basis, the focus of work will shift toward conducting a comprehensive comparison with the outgoing longwave radiation (OLR) data set, a widely used indicator of tropical convection and rainfall. In addition, further intercomparisons will be made among the HRC and OLR data sets and tropical rainfall data. The aim is to determine the usefulness of the HRC data set as an indicator of tropical convection at various time scales.

Pentads of outgoing longwave radiation for the period June 1974 through August 1986 and pentads of 250/850 mb velocity potential (stream function) for the period January 1979 – August 1986 (July 1976 – August 1986) will be added to the CRP data archive.

DIAGNOSTIC CLIMATE STUDIES

Accomplishments FY 1986

Approximately 20 warm and cold events of the El Niño/Southern Oscillation (ENSO) phenomenon during the past hundred years have been indentified. Global composites of sea-surface temperature (SST), sea level pressure (SLP), and surface vector mean winds have been produced over the world's oceans. Also global composite maps of temperature and precipitation signals over land have been produced for both cold and warm ENSO events. These are being used in studies of interannual climate variability associated with the ENSO phenomenon.

To help forecast the onset and establishment of the next ENSO Warm Event, a number of variables are being routinely monitored: (1) equatorial island surface winds (daily summaries), (2) frequency and longitudes of near-equatorial westerly surface winds and the mean longitude of near-equatorial values of the 28.5° C SST isotherm, (3) HRC frequencies and anomalous values of OLR, and (4) 250-mb velocity potential in the tropics. Monthly summaries of global ship reports are also produced within about 20 days of the end of each calendar month.

A multivariate statistical forecasting procedure was developed, which establishes probability limits on the occurrence of arbitrary thresholds in, for example, eastern equatorial Pacific SSTs, using any number of predictors such as current and previous values of the Southern Oscillation, and sea-level pressure indices.

Analysis of precipitation fluctuations over the land areas of the Northern Hemisphere during the past hundred years reveals a secular trend toward higher precipitation in middle latitudes (25°–45°N) compared with a downward trend in tropical latitudes (0°–20°N). Most of the tropical drying trend, however, comes from the continent of Africa, whereas the middle-latitude increase appears to be more zonally uniform. In FY 1986 ESG included the Program for Regional Observing and Forecasting Services, the Weather Research Program, the Weather Modification Program, and the Climate Research Program.

Analyses of temperature variations over the Northern Hemisphere show a very strong signal in the tropics associated with the extreme phases of the ENSO. Temperatures are significantly cooler in the 12 months following the development of an ENSO Cold Event, whereas they are significantly warmer than normal in the 12 months following a Warm Event. The signal decreases in middle-latitude regions and essentially disappears over higher latitudes (>50°N).

Work was completed on a manuscript describing the observed seasonal cycle (annual and semiannual components) of the 250/850 mb winds and comparing it with the seasonal cycle in a 20-year integration of the NCAR Community Climate Model (CCM). The CCM climate was forced by seasonally varying boundary conditions (e.g., sea-surface temperatures) only. It was suggested that the asymmetric component of the observed semiannual harmonic in the tropics is forced by the large-scale tropical land/ocean distribution. The semiannual harmonic in the CCM was substantially different from the observed. The low (modeled) mountains appeared to influence the position and possibly the intensity of the seasonal convection centers (e.g., equatorial Africa and South America) with a tendency for westward displacement relative to the observed. Simultaneously, the "Indonesian" monsoon was located too far north.

The 30–60 day oscillations were a fairly regular feature of the tropical atmosphere, especially from October 1985 through August 1986. In general, the recurrence interval over the Indian Ocean/western equatorial Pacific was in the 30–40 day range. A particularly strong oscillation in January/February of this period was associated with North Pacific circulation anomalies reminiscent of the 1982–83 ENSO event. A marked retreat of convection into the Indian Ocean was observed during March. A composite life cycle of 30–60 day oscillations based on principal components of the tropical velocity potential field was developed. Separate life cycles were described for November–April and May–October. Statistically significant connections with the extratropics are confined to the winter hemisphere.

An analysis was conducted of the effect of interannual variability of Colorado average precipitation and changes in reservoir levels. It was found that reservoir managers attempt to accommodate expected inflows by drawing down reservoirs during expected high-runoff years and maintaining higher than normal late-winter/early-spring levels in anticipation of low streamflows. However, the volume of water that represents the difference between the total annual reservoir outflow and the measured annual range in reservoir levels is inversely correlated with precipitation, reflecting higher water demand during low-precipitation years and vice versa.

Plans FY 1987

Two additional 15-year CCM simulations will be analyzed. In the first simulation a different sea-surface temperature data set will be used to force the model; in the second simulation interannual variability of SSTs will be included. The influence of these different boundary conditions will be assessed.

FY–1987 work will concentrate on analyzing and quantifying the links that appear to exist between the synoptic-scale Westerly Wind/Convection Episodes (WWCE) and the planetary scale 30–60

day oscillations. The association between 30–60 day oscillations and the occurrence of WWCEs over the western Pacific will be examined. Case studies are planned for individual 30–60 day events (one from each of the past eight northern winters) that were associated with major transitions in Northern Hemisphere weather regimes.

We hope to construct a life cycle of the WWCEs associated with the 30–60 day oscillations including their genesis, maturation, and decay phase. The episodical tropical/extratropical links associated with 30–60 day oscillations will also be investigated for each of the case studies. We will attempt to reconcile a Rossby-wave-dispersion description with a jet-extension/contraction description.

We plan to investigate the feasibility of developing a real-time monitoring system that will have access to a global data base. The system will be based on the idea that there are direct links between the location of the major monsoonal center over the Indian Ocean/western Pacific and the intensity of the major wintertime jet streams. Initially, we will design the system to monitor and make experimental outlooks for the major changes that can occur in Northern Hemisphere winter weather regimes.

Analysis of secular climatic fluctuations requires that a measure of any inherent biases in the data be identified and, if possible, accounted for. Work to estimate and adjust for nonclimatic biases will proceed in FY 1987. It is expected that this will lead to a more reliable estimate of global- and regional-scale fluctuations in the surface marine thermal field (air and sea-surface temperature) over the past hundred years.

WEATHER RESEARCH PROGRAM

The Weather Research Program (WRP) conducts research to understand the genesis, structure, evolution, motion, dissipation, and predictability of synoptic-scale and mesoscale weather systems, and to improve forecasts of their attendant weather phenomena such as lightning, high wind, wind shear, excessive rains, and flash floods. WRP actively participates in planning and conducting scientific field experiments involving sophisticated research aircraft and complex networks of remote sensing and conventional meteorological instrumentation. WRP places great emphasis on transferring research results and new knowledge to the National Weather Service (NWS) and the national user community. The three groups in WRP, Mesoscale Convective Systems Group, Thunderstorm Studies Group, and Weather Analysis and Prediction Group, conduct basic and applied research on the following subjects:

- Predictability of synoptic-scale and mesoscale weather systems and attendant significant weather phenomena.
- Characteristics of the synoptic-scale environment and their relations to the structure, intensity, and evolution of subsequent convection.
- Interactions between mesoscale weather systems and both the synoptic-scale environment and cloud-scale processes.
- Evolution of the dynamic and thermodynamic structure of Mesoscale Convective Systems (MCSs), and the nature and intensity of attendant significant weather. .
- Development of airborne Doppler radar technology.
- Application of new remote sensor data for understanding and predicting mesoscale weather systems.

Accomplishments FY 1986

Data analysis proceeded with data from two recent field programs in which WRP was a major participant. The projects were OK–PRE–STORM (Oklahoma-Kansas Preliminary Regional Experiment for

STORM-Central), operated in 1985 from a base in Oklahoma City, and AIMCS (Airborne Investigations of Mesoscale Convective Systems), operated in 1984 from Denver. Accomplishments during FY 1986 follow:

- Analyzed the internal structure of two squall-line cases from OK–PRE–STORM and AIMCS using combined NOAA P–3 aircraft and ground-based Doppler radar data.
- Developed techniques for merging airborne and ground-based Doppler information into a single analysis of cloud structure.
- Analyzed the kinematic structure of two OK–PRE–STORM squall lines with wind Profiler data compared with special rawinsondes collected throughout Oklahoma and Kansas.
- Evaluated the applications program MESO, developed at the Oklahoma City WSFO, for 21 cases of OK–PRE–STORM synoptic events, and offered specific suggestions for its improvement in operations.
- Evaluated the performance of two numerical models produced operationally by the National Meteorological Center (NMC) for 12 convective systems observed during OK–PRE–STORM.
- Developed software for displaying a wide variety of AIMCS and OK–PRE–STORM data by using the VAX computer at WRP.
- Completed an archive of most OK–PRE–STORM and AIMCS data sets, and filled numerous requests for these data from scientists in NOAA, other Federal laboratories, and universities.
- Combined two types of surface wind mesonetwork data into a single data set for all of OK–PRE–STORM over both Kansas and Oklahoma.
- Categorized the Mesoscale Convective Systems (MCSs) observed during OK–PRE–STORM into several types of internal structure, based on radar and upper-air information.
- Completed evaluation of a quasi-operational experiment during the summer of 1984 that sought to forecast MCSs from standard NMC model output.

The study of the Cheyenne flash flood of 1 August 1985 was nearly completed. Detailed radar analysis suggests that the storm was multicellular during the early development stage, and then assumed the characteristics of a rotating supercell. Most analyses of the interaction of processes on scales ranging from the synoptic to meso-beta have been finished.

Interactions of WRP with operational meteorological facilities continued in several areas. Quasi-geostrophic (Q–G) diagnostics began to be computed in real time at WRP and at the Oklahoma City NWS Forecast Office during the summer of 1986. Staff continued to teach courses in flash floods at the NWS Training Center in Kansas City. The cooperative Colorado snowfall prediction study continued with the Denver NWS Forecast Office. Plans were developed to begin daily weather discussions in the fall of 1986, in cooperation with NCAR, PROFS, and the Denver NWS. Interactions concerning lightning research continued with NWS Headquarters, and NWS Western and Southern Region Headquarters.

Kennedy Space Center (KSC) data from the summer of 1985 were analyzed, and results were delivered to KSC for testing by forecasters in the summer of 1986. Maps of lightning climatology for central Florida and the KSC region were developed for six low-level flow regimes. Surface wind data were also analyzed to assess the use of surface convergence for nowcasting cloud-to-ground lightning over KSC. The patterns, probabilities, and timing from the two studies were considered useful by KSC forecasters.

Quasi-geostrophic diagnostics from which inferences can be made concerning the atmosphere's large-scale vertical motion and thermodynamic stability change patterns are now routinely computed for

both synoptic-scale and mesoscale research case studies. For synoptic-scale studies, the diagnostic reveal how similar-appearing flow patterns differ dynamically. For mesoscale studies, the diagnostics suggest the general type of convective storm systems that result from mesoscale processes.

A multiscale analysis was nearly completed of weather conditions at the time of the disastrous airliner crash at Dallas–Fort Worth on 2 August 1985. The parent thunderstorm developed in a dry-adiabatic lower troposphere, and an elevated dry layer was also found above 700 mb. The thunderstorm developed along an outflow-reinforced frontal boundary; then strong downdrafts reached the surface in a hybrid form of wet and dry microbursts.

Three additional microbursts were also studied in collaboration with NWS Forecast Offices. All the storms had features shown to be characteristic of microbursts as shown in recent WRP research, including low-level focusing boundaries, relatively benign radar echoes, and dry layers aloft.

Responses of the atmosphere to imposed heating, distributed spatially and temporally in a manner consistent with the results of diagnostic studies of MCSs, were examined using the WRP two-dimensional numerical model. This led to development of a simple hypothesis linking the long-lasting mesoscale response of the atmosphere to condensation heating in MCSs to the structure of the heating profile.

The mesoscale convective complex (MCC) annual summary for 1985 was completed with the new automated software developed at WRP. The 59 MCCs were documented in nearly real time, and new software was added to provide life history statistics and automatic separation of merged cloud tops at −52°C for distinct mesoscale systems.

Development neared completion of a technique to composite and display observations relative to the more general class of convective systems called MCSs, of which the largest are defined as MCCs. A condensed set of 6 years of radiosonde observations relative to 200 MCCs is the core of the package, and a subgroup of 70 High-Plains MCCs has been analyzed to produce thermodynamic and first-order kinematic quantities.

A rigorous examination began into the role of static stability across a wide range of temporal and spatial scales. Climatological variations in lapse rate are also being evaluated in this study, which includes case examples that concentrate on scale interactions leading to intense convective episodes.

Studies were nearly completed describing applications of biconstituent diffusion theory to some atmospheric phenomena, and derivative estimation from marginally sampled vector point functions.

A study of circulations in MCSs was initiated for several cases exhibiting a residual middle-level circulation in satellite imagery. Large-scale data sets were collected in FY 1986 to begin this study.

The equilibrium-level temperatures of four MCSs on two days, as observed from satellites, were enchanced to correlate the areas above these temperatures with severe weather reports. No correlation was found in this preliminary study, owing in part to the sparsely inhabited region under two of the MCSs.

Several large data sets were collected at WRP during FY 1986. A complete radiosonde data base from 1950 to the present was nearly assembled; most of the checking was completed to make the data hydrostatically consistent, and to check for gross errors commonly found in such large data sets. Another large data set was acquired from the NWS National Severe Storms Forecast Center in Kansas City; all the severe storm forecast areas and corresponding verification reports from 1955 to 1985 are included.

Members of WRP were invited by several foreign agencies and countries to participate in international programs and projects. One member visited the People's Republic of China to give lectures and hold discussions on heavy rain and flash floods. Another was invited to advise the Spanish government on mesoscale and radar meteorology, and on related aspects of modernization of their weather services. One WRP staff member was asked by the World Meteorological Organization in Geneva, Switzerland, to assist in final stages of preparing an international cloud atlas, in part by using photos from other WRP scientists. Several others were asked to assist in planning for the Taiwan Meteorological Experiment.

Plans FY 1987

The research projects investigating OK–PRE–STORM and AIMCS data will expand into several major research areas. One area will examine the NMC model products that were used in OK–PRE–STORM forecasting of MCSs. Another study will analyze the structure of OK–PRE–STORM squall lines with wind Profilers and supplementary radiosondes. Airborne and ground-based Doppler and conventional radar data will be used to document the internal structure of MCSs during AIMCS and OK–PRE–STORM. Additional studies will categorize MCSs by their internal structure as observed by radar and indicated by other data. Surface winds from the mesonetworks will be studied to show the low-level flow distributions during the life cycle of MCSs. Cloud-to-ground lightning data will be related to many of these data sets for several cases in OK–PRE–STORM. Throughout FY 1987, software for displaying project data on the VAX computer at WRP will be developed, and archives of the data set will be maintained for use by WRP and other interested scientists.

The study of the Cheyenne flash flood on 1 August 1985 will be completed, to define the processes on all scales contributing to this stationary heavy rainfall event.

Staff of WRP will continue to interact with NWS in a wide variety of activities. Courses on flash floods will be taught at the NWS Training Center in Kansas City, quasi-geostrophic diagnostics will be evaluated at the Oklahoma City Forecast Office, the Colorado snowstorm study and daily weather discussions will be conducted jointly with the Denver WSFO, and lightning studies will be developed and discussed jointly with several NWS facilities.

Cloud-to-ground lightning over Florida and Colorado will be analyzed by flow regimes for several summers to identify the distributions of flashes by time of day, and to understand the meteorological factors influencing convection, including relations between radar and lightning parameters, for use by forecasters and others in these areas.

Surface convergence will be related to lightning and radar data from two summers in the KSC area to develop an operational lightning forecasting method, in cooperation with forecasters and staff at KSC.

Quasi-geostrophic studies in FY 1987 will include diagnostics in climatological studies, automating the data ingest process to allow twice-daily diagnosis of current weather patterns for special forecasting projects, and incorporating the geopotential tendency (a part of quasi-geostrophic theory) into the computation algorithm.

Research will be completed on the Dallas–Fort Worth microburst involved in the airliner crash on 2 August 1985. The final study, combining analyses on multiple scales, will be published and distributed widely to aviation interests within NOAA and elsewhere. Comparisons of this case will also be made with other microburst events to evaluate the possibility that environmental clues within currently available data may be used to indicate microbursts on a limited number of days.

The nested-grid model, now run operationally twice daily at NMC, will be installed on the CYBER–205 at the Consolidated Scientific Computing System in Gaithersburg. This is the beginning of a multiyear effort to study the performance of the model in predicting heavy precipitation events and other weather events in which mesoscale processes have an important role. The goal of this research is to develop model improvements that can be incorporated operationally.

The automated MCS software will continue to be used to document the life history of mesosystems during AIMCS and OK–PRE–STORM, for producing annual summary articles for MCCs occurring in 1985 and 1986, and for developing other statistics related to the life cycles of MCSs.

Composites of MCC environments will be made during FY 1987 to compute vorticity and momentum budgets based on radiosonde data collected in the vicinity of 200 MCCs over the United States.

The study of residual middle-level circulations in MCSs will continue through identification of several cases and analysis of large-scale data sets in their vicinity.

The construction of several large data sets will be completed in FY 1987: (1) All radiosonde data from 1950 to the present will be checked and combined into one data set; (2) severe weather forecast areas and verification reports from 1955 to 1985 will be combined for an in-depth study of thunderstorm forecasts; (3) Manually Digitized Radar data from NWS radars, and Hourly Precipitation Data will be compared with the forecast and verification information, with a long-term view toward improving convective forecasts.

International contacts, all of them resulting from invitations by foreign agencies and governments, will continue. Two members of WRP will participate in the Taiwan Meteorological Experiment in the spring of 1987. Two members will visit Spain to advise the Institute of Meteorology on its modernization program and to give lectures on radar and severe weather. One member will visit the World Meteorological Organization in Geneva to complete arrangements for publication of an international cloud atlas, using material supplied in part by WRP. Interactions will also take place between WRP and the People's Republic of China on topics related to the forecasting of significant weather attendant to large mesoscale convective systems.

PROGRAM FOR REGIONAL OBSERVING AND FORECASTING SERVICES

The mission of the Program for Regional Observing and Forecasting Services (PROFS) is to improve operational weather services by testing and transferring advances in science and technology. PROFS, using the results of atmospheric and systems research, develops operationally feasible forecast technology that incorporates observations, computer processing, and human interaction. PROFS integrates capabilities into specific systems, then tests and evaluates those systems in forecasting exercises.

PROFS works closely with the weather research community—for example, with the National Center for Atmospheric Research (NCAR)—soliciting ideas on forecasting workstations and consulting on plans for test exercises. PROFS also works with the three major operational weather services: the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the U.S. Air Force Air Weather Service (AWS). Two NWS employees are PROFS senior staff members, providing coordination with the Advanced Weather Interactive Processing System for the 1990s (AWIPS–90).

Of the numerous important PROFS activities for FY 1986, the Denver AWIPS–90 Risk Reduction and Requirements Evaluation (DAR^{3}E) project was the most pervasive. Personnel from each branch of PROFS participated in the planning, design, implementation, and support of the advanced interactive forecaster workstation installed at the Denver Weather Service Forecast Office to provide NWS with a test-bed for many functional capabilities planned for the AWIPS–90 system. PROFS continued to provide support for the Center Weather Service Unit at the FAA's Denver Air Route Traffic Control Center (ARTCC) by installing an upgraded forecaster workstation and data communications system. For NEXRAD (Next-Generation Weather Radar), a joint program of NWS, the FAA, and the U.S. Air Force, PROFS coded and tested algorithms to be used in the new national Doppler weather radar system. In cooperation with the National Environmental Satellite, Data, and Information Service (NESDIS), Colorado State University, and the University of Wisconsin, PROFS investigated ingest and product generation methods for VISSR (Visible and Infrared Spin-Scan Radiometer) Atmospheric Sounder (VAS) satellite data. PROFS supplied data and hardware to support National Severe Storms Laboratory (NSSL) research efforts, and provided workstation evaluation and product development support for U.S. Air Force Space Division meteorological satellite efforts. In cooperation with the Navy and National Ocean Service, PROFS planned the development of a forecaster workstation for the Navy/NOAA Joint Ice Center.

As part of its technology transfer mission, PROFS presented information, tours, and demonstrations to as many as 100 visitors per month from Federal agencies, universities, private industry, and foreign countries. PROFS personnel actively participated in the exchange of information in the environmental

science community with the publication of more than 40 articles, reports, and papers con- cerning PROFS activities and research during FY 1986.

EXPLORATORY DEVELOPMENT FACILITY

The Facility branch is responsible for the design, development, upgrade, operation, and maintenance of the PROFS Exploratory Development Facility (EDF). The EDF consists of the computers, data-ingest interfaces, communication links, and display devices that allow the testing and evaluation of advanced weather information systems. It has been undergoing continual upgrade and improvement since the beginning of PROFS. The system acquires and stores a large variety of meteorological data, analyzes and processes the data into products, and displays the products to forecasters using interactive workstations. The EDF also supports research activities at several ERL, NCAR, and university laboratories by providing data collected by the PROFS system.

Accomplishments FY 1986

The PROFS central facility was upgraded by including a fourth processor, a VAX–11/750, in the VAXcluster configuration. With this upgrade, all major PROFS computers in Boulder have rapid access (70 megabits per second [Mbps] maximum data transfer rate) to the clustered mass storage devices (disk and tape drives). A second Hierarchical Storage Controller (HSC) was installed both to improve overall data-access performance and to provide backup in case of an HSC failure. The procurement and installation of additional disk drives on the cluster increased the total on-line data-storage capability to about 5 gigabytes. A significant increase in system reliability was obtained by introducing volume shadowing in the VAXcluster. By providing a "hot" standby disk, shadowing allows the system to tolerate disk failures without disrupting the flow of real-time data or software development. Efforts were initiated to separate the real-time operational portion of the system from the developmental portion. For example, a disk drive containing all real-time data-acquisition and product-generation software was set up separate from the disk used for software development. Carried further, this type of separation will enhance the reliability of the operational system.

The PROFS, Colorado State University, NCAR, and ERL Laboratories DECnet network containing over 70 nodes (computers) was subdivided into five areas. The subdivision allows the desired independence and isolation of the participating groups, but still provides the necessary interconnectivity for exchanging data and software. The speed of several interconnecting data links was increased substantially and network security was much improved.

To better support the increasing number of PROFS data and product users, EDF has undertaken the development of general-purpose information distribution software, called Communications Services (CS). The main purpose of CS is to provide efficient means for exchanging control messages and data among processes running on the same, or possibly widely separated, computers. The design of CS inherently includes support for simplex, broadcast-type data distribution. Initial testing of CS revealed much improved Central Processing Unit (CPU) utilization on the sending computer, especially when data are distributed to several workstations simultaneously.

A new, enhanced data-ingest interface using a MicroVAX computer was developed to acquire NWS Automation of Field Operations and Services (AFOS) data from both lines (Denver-Cheyenne and Denver-Omaha) of the Central Region distribution circuit. In addition to acquiring significantly more data than the earlier system, the new interface provides notification and data directly to the DAR^{3}E workstation host computer and VAXstation text device.

EDF contributed to the development of the DAR^{3}E system in a number of additional ways. EDF staff worked with the PROFS Experimental Forecast Systems branch to design the workstation furnishings and implemented them at the Denver NWS Forecast Office. The DAR^{3}E workstation computer and display

hardware were configured, tested, and placed in operation at the Forecast Office. A high-speed (448-kilobits per second [kbps]) communications link was installed to ensure timely distribution of data and products from the Boulder central facility to Denver.

In further support of the DAR^{3}E project, EDF initiated 24-h operator coverage of the central facility. The operators are assisted by a new version of the System Activity Monitor (SAM), developed by the SDI (System Design and Implementation) branch. EDF has rewritten and upgraded the Data Acquisition Monitor (DAQMON) and incorporated it in SAM. To provide timely notification to the operators in case of a subsystem failure, a text-to-speech synthesizer system called DECtalk was attached to SAM/DAQMON. DECtalk generates a verbal message in case a failure condition is detected, and broadcasts it throughout the facility, using strategically located loudspeakers. The user's guide to the computer facility was updated and substantially expanded. A new guide aimed at helping both established and new users of the PROFS VAX/VMS system was produced.

The EDF deployed a MicroVAX II-based computer hardware and communications upgrade for the FAA Denver ARTCC in Longmont, Colorado. A real-time demonstration workstation was set up at the Second International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology in Miami, Florida, and EDF supplied the data to it from the Boulder central facility. Operational support of the Profiler Hub continued during the year. The EDF arranged accommodations for installing the second Profiler computer, a VAX–11/780, and provided advice and support to the Profiler staff on incorporating this machine in the network.

Extensive consultations were carried out with the Navy-NOAA Joint Ice Center (JIC) staff concerning the development of a PROFS-type workstation for sea ice analysis and forecasting. Toward the end of FY 1986, JIC accepted the PROFS-proposed approach and the JIC project was initiated.

EDF provided a broad spectrum of support for researchers. Real-time data ranging from PROFS mesonet to satellite images were made available through digital data links to NCAR, CSU, Metropolitan State College, NASA Goddard Space Flight Center (to support the Genesis of Atlantic Lows Experiment [GALE]), and ERL's National Severe Storms Laboratory, Wave Propagation Laboratory, Aeronomy Laboratory, and Weather Research Program. In addition, many data requests were serviced from the PROFS data archive.

Plans FY 1987

- Perform a major upgrade of the PROFS computer facility by installing a 12-million-instructions-per-second (MIPS) VAX 8800 processor on the VAXcluster.
- Continue separating operational and development functions of the facility by installing a second Ethernet local-area network dedicated to operations. Perform network design and planning to incorporate new interconnect technologies such as bridges and gateways for establishing connections to DEC and non-DEC equipment. For example, a design to interconnect the PROFS and National Meteorological Center (NMC) computer facilities will be developed.
- Upgrade one or more data-acquisition interfaces such as Lightning, Pilot Reports, and Mesonet to MicroVAX processors.
- Complete the development of Communications Services and implement it for distributing all PROFS data and products.
- Design and develop hardware and software for the Navy-NOAA Joint Ice Center system.
- Support the wind Profiler demonstration network Hub by operating and maintaining the Hub VAX–11/750 and VAX–11/780 computers and by providing data to the Hub for comparison and quality checking.

- Support research activities at NCAR, CSU, and ERL Laboratories by providing real-time and archived PROFS data sets.

EXPLORATORY DEVELOPMENT GROUP

The mission of the Exploratory Development Group (EDG) is to investigate, implement, and evaluate new technologies that might be available to the operational forecaster in the future. New sensors being evaluated include Doppler radar, VAS satellite, and the wind Profiler; other new technologies being evaluated include artificial intelligence (AI). EDG not only studies these new tech–nologies but also prepares products from them for use in an operational environment.

Accomplishments FY 1986

SATELLITE PROGRAM

The satellite group within EDG continues to progress well in ingest system design and product development using VAS data. Half of this group will join the Forecast Research Group beginning in FY 1987. Development of sounding retrieval algorithms will continue within EDG.

Data Ingest

The satellite ingest group has stayed ahead of planned format changes in satellite data transmission. An innovative data acquisition system, which implements these changes while allowing flexibility in product generation in the ingest stage, has been designed.

The PROFS Geostationary Operational Environmental Satellite (GOES) Data Acquisition System (GDAS I) has routinely ingested GOES Mode A data since August 1982 and Mode AA data since November 1984. By early 1987 both transmission modes will be replaced by Mode AAA. GDAS I can ingest Mode AAA data in a "compatibility mode," which takes advantage of the upward compatibility in the change from Mode AA to Mode AA, but does not utilize all the features of Mode AAA. GDAS II, with a full Mode AAA capability and better overall performance, is being designed.

VAS Project

The PROFS 1985 VAS product evaluation study continued with documentation of one case, plus ancillary observations obtained during the 1985 PROFS Real-Time exercise (RT85).

New products were prepared for the DAR^{3}E workstation to be deployed in FY 1987. These products include a modified upper-level water vapor image that incorporates cloud detail and the capacity to produce VAS soundings in real time on PROFS hardware. VAS soundings are now produced with a physical retrieval algorithm similar to the one used at the University of Wisconsin (Madison). Soundings are computed for each grid location in the Mesoscale Analysis and Prediction System (MAPS) surface analysis or at sites for which surface conditions are known. Improvements in cloud screening techniques have led to an increase in sounding reliability on the national scale. Work is under way to produce analyses of water vapor and temperature that incorporate the structural detail available in VAS data.

RADAR PRODUCTS

The radar products group completed the design of a MicroVAX II/VAXELN-based radar subsystem. Volume 1 of the system specifications document, System Requirements and Concepts, was completed; this document guided the system design. Five functional areas are described in the document: data acquisition, product generation, event handling, system monitoring, and distribution. Event handling and system monitoring, two of the functional areas that define the context in which the subsystem operates, were

designed and implemented. The software portion of the data acquisition functional area was also completed, and system throughput was tested.

Hardware for the system was selected, procured, and partially configured. Modifications began on the microwave data link and calibration preprocessor.

A new radar product development, the RT85 Precipitation Type/Intensity product using dual polarization data, was reformulated and tested. Additionally, an analysis of operational weather radar sensitivities was completed.

NEXRAD

EDG completed its fourth year of Next-Generation Weather Radar (NEXRAD) work. By the end of FY 1986, we will have validated 23 algorithms, nine in FY 1986 alone: Storm Extrapolation Map, the five algorithms in the Precipitation Sequence (Precipitation Preprocessing, Rate, Accumulation, Adjustment, and Products) and the three Radar Data Processing (RADAP) algorithms (Vertically Integrated Liquid Water, Echo Tops, and Severe Weather Probability).

In 1986, we also conducted parameter sensitivity studies on the Storm Sequence, Mesocyclone, Tornado Vortex Signature, Combined Shear, and Cross-Correlation Tracking algorithms. Meteorological assessment was also done for Combined Shear.

ARTIFICIAL INTELLIGENCE

The AI program has implemented two expert systems in an attempt to develop an understanding of the potential for and the problems associated with the use of AI in NWS operations.

The first system predicts the production of hail from an observed thunderstorm. As input, this system uses Doppler radar data and a product (Z_{DR}) derived from dual-polarization Doppler data. Output from the system is a classification of the thunderstorm, ranging from nonsignificant to severe.

The second system monitors the operation and performance of WPL wind Profilers. Wind Profilers are sensitive to occurrences that may result in data degradation. It is important to identify equipment problems that can be corrected by maintenance as opposed to weather-induced temporary data degradation. This system uses two forms of input, the 13-h wind profile plots and the power return plots from the Profiler system.

Both AI systems are under test and evaluation. Initial results indicate that both perform at a level equal to that of human experts.

A third system is being developed to diagnose problems with the POWER workstation. This system will allow remote workstation problems to be diagnosed in a time- and cost-efficient manner.

Plans FY 1987

SATELLITE PROGRAM

- Produce and evaluate real-time VAS soundings on the MAPS grid scale.
- Collect operational soundings through the scheduler.
- Improve temperature and water vapor analyses by merging gradient information from VAS images and soundings.
- Monitor VAS product quality on the DAR^{3}E workstation.
- Evaluate VAS products during the cool season in conjunction with PROFS daily forecast discussions.

- Continue preparation for the mode AAA format change.
- Design MicroVAX II ingest applications for remapping and image processing.
- Assist in implementing a research applications procedure for satellite data archiving.

RADAR PRODUCTS

In FY 1987, the radar subsystem will be completed and used in the DAR^{3}E exercise; Doppler radar data will be acquired by the NCAR CP–2 radar, processed by the radar subsystem, and transmitted to the NWS forecaster workstation in Denver. The functional areas of product generation, product distribution, and data acquisition will be completed. Software and hardware will be configured, and system testing will be carried out with live radar data. Finally, the system will be integrated with the PROFS workstation. Procedures will be identified and implemented to assist in the evaluation of specific products.

NEXRAD

The work plan for NEXRAD includes validation of more algorithms, possibly a Downburst algorithm and the Flash Flood algorithms. Work will continue on meteorological assessment and parameter sensitivity studies of Mesocyclone and Tornado Vortex Signature, as well as the Layer Composite, Cross-Correlation Tracking, and Storm Extrapolation Map Sequence, including a comparison of this sequence with the Storm Sequence.

ARTIFICIAL INTELLIGENCE

The major goal of the AI program is to continue to build, expand, and evaluate heuristic-, scenario-, deep-, and mixed-model expert systems. The information gained will contribute to the eventual success of the transfer of AI technology to NWS. Additionally, a study of alternatives to the use of confidence or certainty factors assigned to rules ("fuzzy" sets) and the possibility of using other languages (LISP, PROLOG, etc.) will be undertaken.

ANALYSIS AND PREDICTION BRANCH

The Analysis and Prediction Branch processes surface and tropospheric data from diverse sources to present a clear picture of atmospheric conditions and to make very-short-term predictions with efficient numerical models. The results of this labor appear on the PROFS workstation during real-time forecast exercises and are expected to benefit aviation and the general public in the form of better weather information. There are two major activities in the branch: development of a MAPS and support of the FAA Central Weather Processor Program.

Accomplishments FY 1986

MESOSCALE ANALYSIS AND PREDICTION SYSTEM

Observational data to support frequently updated tropospheric analyses will be available near the end of this decade. The need for these analyses is vital. The diverse data sources—satellites, ground-based profiling systems, aircraft, and rawinsondes—dictate that the algorithms for analysis be complex and adaptable to change. Short-range predictions based upon these analyses are also needed to fill the present gap 1–2 h ahead, when extrapolative techniques cease to work, and 12 h ahead, when model output from NMC provides guidance. MAPS is a multiyear program for filling these needs; it is fully coordinated with plans of NWS. Its long-term goal is to provide detailed analyses of diverse surface and tropospheric data over the contiguous 48 United States and very-short-term local predictions.

A surface analysis package was added to MAPS in June. It generates gridded fields of sea level pressure, potential temperature, wind, and dew point, based upon hourly Surface Aviation Observations (SAOs). The analysis of sea level pressure is based upon altimeter setting because that is the most frequently reported parameter in the SAO. A correction for reduction of pressure to sea level was added in August, to improve the analysis over mountainous terrain. Potential temperature is analyzed because it is less subject to variations in elevation than temperature itself. The analyses of surface dew point and wind show forecasters where low-level moisture is concentrated and where it is moving.

Quality control routines were improved throughout the year. They range from simple checks for reasonable values to checks for hydrostatic consistency in sounding data to sophisticated horizontal "buddy" checks based upon optimal interpolation. The most complicated checks of all are applied to hourly wind Profiler data; these include both time and space dimensions. It is noteworthy that the MAPS team is responsible for developing quality control software for the demonstration network of 30 wind Profilers scheduled for installation in the U.S. Midwest late in this decade.

In its first realization, MAPS analyzed geopotential height, wind, temperature, and relative humidity on eight mandatory pressure surfaces. The pressure coordinate upper-air analysis scheme was made more accurate while computing time was reduced by a factor of 3. Work is now well under way toward a new version of MAPS on constant potential temperature (isentropic) surfaces. This step is being taken because fronts, short waves, and other atmospheric features tend to be better defined on surfaces of constant potential temperature and, in fact, air flow remains on these surfaces in the absence of diabatic processes. Tests of this new system have begun. The prediction model that couples the analyses in time (essentially extrapolating the atmospheric state forward) is an isentropic primitive equation model. Extensive testing is planned in FY 1987.

A joint modeling effort between PROFS and NCAR started with a model simulation study of local surface conditions in northeastern Colorado. The study revealed that similar circulations may often develop in topographically similar regions along the Front Range where observations are sparse.

SUPPORT OF FAA'S CENTRAL WEATHER PROCESSOR PROJECT

The Central Weather Processor (CWP) is being developed by the FAA for the communication of timely weather information to meteorologists and air traffic controllers at ARTCCs around the country. For several years, a group within the Analysis and Prediction Branch has designed and tested products for the CWP and has reviewed numerous planning documents in the light of PROFS experience in building meteorological workstations.

With the aid of pilot reports collected during most of the past year, the CWP team completed an evaluation of algorithms for the detection of rime icing, clear air turbulence, and cloud top height. Because the icing and turbulence algorithms depend upon analyses of 0000 and 1200 GMT rawinsonde data, we could use for verification only those pilot reports within an hour or two of 0000 and 1200 GMT. Despite the long collection period, the data sample was disappointingly small, though still large enough to permit an evaluation. We concluded that further work on a turbulence algorithm is unwarranted at this time and that the icing algorithm should be improved by accounting for cloud-base and cloud-top heights (available from surface and satellite observations, respectively) and maps of radar reflectivity. The cloud-top algorithm will be implemented in CWP, probably as a color image; we supplied Program Design Language (PDL) for this product in September.

A final report on the Instrument Flight Rules (IFR) Area Outline was submitted in late June. This product, based on satellite and surface observations, objective analysis, and statistical regression, shows where low ceilings and visibilities may be expected. It marks an improvement over the existing operational Weather Depiction chart. Extensive testing suggests it to be a good candidate for the CWP.

In late January and February, we configured a workstation to display candidate CWP products in real time. Each day, we used the CWP upper-air-sounding analysis program and grid-sectioning routines to

compare the gridded output of CWP algorithms with very recent or current pilot reports. This testing suggested a number of improvements to the algorithms, many of which were made on the spot.

The equilibrium level product is new this year. In the form of a color image, it shows the departure of actual cloud-top temperatures from the temperature at the equilibrium level, where vertical velocity within a thunderstorm reaches a maximum. The computations are based on parcel theory, upper-air sounding data, and surface temperature, pressure, and dew point. We have found that the properties of low-level airflow seem to be as important for the maintenance (or demise) of large thunderstorms as changes in cloud top area at temperatures below that of the equilibrium level. On the other hand, a map of equilibrium-level temperature is valuable in itself. A careful evaluation of this product is warranted.

Plans FY 1987

MESOSCALE ANALYSIS AND PREDICTION SYSTEM

The Short–Range Prediction Branch at NMC and the Analysis and Prediction Branch at PROFS have agreed to pool resources to development a system for frequent analyses of asynoptic, tropospheric data, which will ultimately run operationally at NMC.

The system will rely primarily on (1) wind Profiler data from a new network of 30 UHF radars to be installed in the U.S. Midwest beginning in December of 1988, (2) aircraft reports (primarily automated), (3) surface aviation observations, and (4) rawinsonde data twice a day. The inclusion of satellite soundings in this system is questionable because there is no guarantee that the retrieved soundings can be supplied in time for quick analyses and because it is not yet clear how to combine satellite soundings with other kinds of information.

The assimilation system will be based on optimum interpolation, a statistical approach to the analysis of weather data, and will include both objective and subjective forms of quality control. It is being programmed at PROFS but will ultimately run on computers at NMC. The cycle time will be 3 h initially and then 1 h. The analyses are designed primarily for real-time diagnosis and nowcasting rather than as input to numerical prediction models. A major goal is to supply line forecasters with new analyses within 1 h of observation time.

In early tests of the system, an isentropic, primitive-equation model will be used for the assimilation. The model will contain only the essential dynamics and very little parameterization of physics so that it will run quickly on a medium-size computer. Despite its simplicity, the model should produce a reasonable very-short-term forecast. The system should become operational around 1990.

Improvements in the quality control of wind Profiler data will be made in three areas:

- Expand the basic versions of the checking software to include more information (for example, data from rawinsonde reports and Profiler returned-power data) and use information about the climatological variability of wind with height and by season. Time-height optimal interpolation is ideally suited for incorporating this information in error checking. Preliminary tests of this technique gave encouraging results, but many possible refinements remain to be explored. Although the code will need to be streamlined before it can run in real time for all stations in the network, it can still serve as a standard for comparison with other error-checking methods.

- Continue to transfer the development code to documented, stable, real-time operating versions. The real-time versions will run on the Hub computer, which processes all incoming Profiler information, and on the PROFS computer, which generates real-time products for an experimental workstation at the Denver Weather Service Forecast Office.

- Continue subjective monitoring of quality control algorithms to fine-tune them and devise improvements.

During the next two years, the MAPS team will aid in developing a training program for NWS forecasters on the use of wind Profiler data. The program will consist of four videotapes with accompanying training manuals on the following subjects: operation of the wind profiling radar, quality control of wind Profiler data, and use of wind Profiler data in summertime and wintertime forecasting. The first two videotapes will be available by the end of FY 1987.

MAPS will continue to work with NCAR and during FY 1987 will assemble a 4-day data set of all available observations to be used in regional data assimilation studies. A computer link will be developed between the MAPS ingest/quality control/analysis system and the NCAR/Penn State mesoscale model to test assimilation techniques.

SUPPORT OF FAA'S CENTRAL WEATHER PROCESSOR

PROFS will continue to support the operation of a workstation at the Denver ARTCC, located in Longmont, Colorado, and new products are to be developed for that workstation:

- Vertical cross sections based directly upon rawinsonde data.
- A background map of the Denver ARTCC's area of responsibility showing the location of each Very High Frequency Omnidirectional Range collocated with Tactical Air Navigation (VORTAC).
- A "read-cursor" function that returns the distance and direction to the nearest VORTAC.
- A plot of data from the Low Level Windshear Alert System (LLWAS) surrounding Stapleton Airport (with background map).
- Radar displays compatible with plots of LLWAS data.

IFR Area Outline product and cloud top algorithm, already tested at PROFS, will be implemented on the ARTCC workstation. Data from NCAR's CP-2 10-cm Doppler radar will also be added when that radar is operating. Meteorologists from PROFS will occasionally work shifts alongside ARTCC meteorologists to evaluate these products and to become more familiar with the ARTCC mission and daily workload.

The FAA has requested that PROFS develop an improved icing product. The old product made use of a "D-value," which indicated the likelihood of rime icing for a given temperature and dew point depression. Much more information relevant to icing is available in the form of infrared satellite images from which cloud-top temperatures may be inferred, surface observations of clouds and pre-cipitation intensity and type, and maps of radar reflectivity. Efforts to incorporate this information into an improved icing product will begin in FY 1987.

EXPERIMENTAL FORECAST SYSTEMS

The Experimental Forecast Systems (EFS) branch is primarily responsible for specifying requirements for advanced meteorological workstations, developing products, and managing the effort to field advanced meteorological systems. EFS also provides support for research and on-going support for real-time systems.

Accomplishments FY 1986

DAR^{3}E

The primary effort in EFS during the past year was the development of the DAR^{3}E workstation. At the request of the NWS, PROFS has incorporated many capabilities specified for AWIPS-90 into the

workstation. DAR^{3}E will provide critical feedback on the importance and utility of some AWIPS–90 functional capabilities. It will also provide potential contractors a look at a system that meets many of the requirements specified for AWIPS–90.

Previous PROFS workstations have been designed primarily to address mesoscale weather phenomena. Since the DAR^{3}E workstation will be used by forecasters at Denver WSFO to issue public forecasts for 5 days, DAR^{3}E must incorporate the traditional synoptic and large-scale information available over AFOS. To accomplish this, three new scales were added for a total of eight. Images and graphics are available for scales ranging from the Northern Hemisphere down to northeast Colorado. A full complement of AFOS graphics (300) can be displayed on any of four scales in combination with satellite or radar images, data plots, and other graphics. Most AFOS graphics use a polar stereographic projection. These can be displayed on any of four polar stereographic scales in the DAR^{3}E workstation: Northern Hemisphere, North America, National (continental United States), and Rocky Mountain region. Graphics can be displayed in normal resolution (512 x 512 pixels) or high resolution (1024 $\times$ 1024) for enhanced detail.

To support hand analysis by the forecaster, several new plots will be provided. Upper-air plots at mandatory pressure levels are provided on two scales, North American and National. These are produced twice daily shortly after rawinsonde data are recieved. An hourly plot of surface observations is also provided. The plot covers the western United States and uses most available data. Hardcopy plots can be quickly produced on a laser printer using regular paper, without loss of detail.

To aid in issuing forecasts for Colorado, a new scale encompassing the state and bordering areas was created. Full-resolution (1-km) visible satellite images are produced for this scale in addition to infrared and water vapor images. A mosaic of the Cheyenne and Limon radars provides radar information for more than half of the state scale. Surface observations can be superimposed on any of these images. High-resolution graphics on this scale depict observed maximum and minimum temperatures and 24-h precipitation for all daily climate reporting points in Colorado. Other graphics display model output statistics guidance for temperature, winds, cloud cover, etc., on the state scale map. All these graphics depict traditional guidance in a new, easy-to-use form for preparing public zone forecasts.

New capabilities in the DAR^{3}E workstation will assist forecasters during severe weather. As severe weather watches and warnings are issued, outlines of the affected areas are created on the state scale. Watches and warnings for bordering counties will alert forecasters to potential problem areas and allow them to monitor the warning area superimposed on satellite or radar images. If severe weather threatens a forecaster's own area of responsibility, a text generation capability will support rapid and easy creation of severe thunderstorm, tornado, or flash flood warnings. The forecaster simply draws a box on a satellite or radar image encompassing the severe weather and the warning message is automatically created. Warnings created in this manner have the additional advantage that the exact warning area can be recreated. The precise latitude and longitude of the warning area corners are saved and can be included as part of the warning message. Thus any user receiving the warning could reconstruct the actual warning box outlined by the forecaster, saving valuable coordination time.

A significant improvement in graphics display has been developed for DAR^{3}E. Previously, graphics were called up one at a time. "Family graphics" group up to 56 separate, but related, graphics together. Normally seven graphic fields form an individual family member. Eight members are combined to form a family, each one representing a separate time step, either an analysis or forecast. When these are looped on the workstation, the evolution in time of the displayed fields is depicted. The seven fields can be toggled on or off in any combination. Family graphics help the forecaster to assimilate and evaluate numerical model guidance quickly. Families are generated for the Northern Hemisphere, North America, and National scales and represent each of the four main NMC models. Two special families compare the numerical model forecasts.

Greater flexibility in calling up products has been added to the DAR^{3}E workstation. Previous versions of any product can be displayed in combination with any image or graphic. This capability is particularly

useful for verifying earlier forecasts with subsequent analyses and satellite imagery. This provides insight into numerical model performance, an important factor in utilizing numerical model guidance.

A new interface device and a new menu were designed for DAR^{3}E. The most common display controls (zoom, loop speed, toggle buttons for image and graphic overlays) are now grouped with a trackball, bringing the most frequently used functions together in a single unit. One such device is connected to each display providing independent display manipulation. The menu was substantially revised. The independent display now used will provide fast response and allow both graphic/image displays to have loops of 4, 8, 16, or 32 frames. The method of product selection from the menu was changed to a two-step (select then load) process. This will provide more error-free operation and the capability to load images without reloading displayed graphics.

To support the display of text information and the creation of forecasts and other text products, a totally new text facility was developed for DAR^{3}E. It is connected to the Denver AFOS system and retrieves and stores text information from the AFOS data base. The text portion of the workstation features four windows for general purpose display and text editing. All four windows may be open simultaneously, each displaying different information or performing a different task. A fifth window is reserved for incoming alarm and alert information, allowing the forecaster to see the list of alarm products received without having to request them. A sixth window is dedicated to receiving warnings initiated on the graphic/image displays. The independent operation of the windows allows a forecaster to suspend work on a forecast, edit a warning, and then resume work on the forecast without waiting to store and retrieve products.

A "browser" menu was developed for the text facility to provide a fast and user-friendly interface to AFOS. The user can access any product or AFOS command through this tree-structured menu by simply making a series of selections. An AFOS command line facility is also provided, allowing a user to type an AFOS command as on an AFOS terminal. A unique feature of the text facility is the automatic updating of surface weather observations. When selected by the user, displayed observations are automatically updated on the screen as new observations arrive. This is an important feature for monitoring changes in weather conditions.

Finally, a powerful and sophisticated text editor/word processor was developed for the text portion of the DAR^{3}E workstation. This allows the forecaster to create forecast and warning products quickly and easily.

RESEARCH SUPPORT

A workstation based on a MicroVAX II minicomputer and a Ramtek model 9465 display system was developed for and deployed at NSSL in Norman, Oklahoma, in the spring of 1986 to provide research support for NSSL's late-spring/early-summer field program. Real-time data received and processed at PROFS were transmitted on dedicated telephone lines. These data included NMC graphics, satellite imagery (VISSR and VAS), surface observations, soundings, and Profiler wind data from WPL's Norman site.

Real-time operations were supported from 15 April until 15 June. During that period, data for several case days were archived at PROFS. In late June, data for one of these cases were transmitted to Norman, for retrospective analysis. A surface analysis program, tailored to the Oklahoma area, was made available to NSSL research meteorologists. They modified the analysis parameters for their specific needs and displayed the results on the workstation in concert with other data. Data for several other cases were transferred to Norman on magnetic tape in late July.

PROFS collected and archived data for GALE, which was carried out from 15 January through 15 March on the east coast of the United States. PROFS support for this experiment consisted of providing upper-air data received through AFOS to the NASA Goddard Space Flight Center (GSFC). Routine and special (3-h) soundings were disseminated by AFOS during GALE. PROFS developed software to store these in its data base and format them in ASCII (tabular) form. GSFC researchers then dialed in to the

PROFS system and retrieved these data in near-real time. Research Support funds also paid the salaries of two PROFS employees during 1-month assignments to GALE.

Plans FY 1987

During FY 1987, EFS will manage the operation, evaluation, maintenance, and evolution of the DAR^{3}E system.

DAR^{3}E will receive 24-h support from PROFS. This support includes the operation and maintenance of the three major DAR^{3}E subsystems: data ingest, product generation, and forecaster workstation. Support staff will be on duty and on call at all times.

EFS will be responsible for managing the comprehensive DAR^{3}E evaluation effort. The feedback from the DAR^{3}E evaluation will support AWIPS–90 System Specification activities and transition planning for modernization and restructuring.

Software support for DAR^{3}E in the form of maintenance and minor upgrades will be managed and carried out by the EFS staff.

In addition, the planning, design, and initial development activities for DAR^{3}E phase II will be undertaken by EFS, with completion and implementation in the Denver Weather Service Forecast Office targeted for October 1988. This effort is a critical piece of the NWS modernization and transition planning effort and will constitute a significant commitment of PROFS resources.

Research support will continue as in previous years. Support is planned for NSSL spring exercises, and for field experiments to be carried out in the Denver area by CSU, NCAR, and others.

SYSTEM DESIGN AND IMPLEMENTATION

The System Design and Implementation (SDI) branch defines functional specifications for new workstation systems. The specifications provide the basis for system design and definition of specialized hardware configurations. SDI employs such techniques as structured system analysis and design (popularized by DeMarco) and the technique of information hiding (espoused by Parnes) to arrive at final software designs.

Once a design has been completed, SDI has prime responsibility for the development of the workstation control environment, consisting of such functions as file manager, user interface, applications executive, events handler, and display manipulation (excluding meteorological applications). Development of applications software is the responsibilty of other groups within PROFS. Additionally, SDI provides the scheduling environment for the generation of routinely generated meteorological products and has responsibility for the integration and check-out (but not validation) of newly developed software for the system.

SDI works with other government agencies, such as the U.S. Air Force, to provide enhancements to existing workstations and provides consultation on system design issues.

Accomplishments FY 1986

In December 1985, SDI developed the initial version of the PROFS Operational Weather, Education, and Research (POWER) system. The POWER system is designed for researchers with a need to process and display real-time data and also for those who have a need to review and analyze specific data cases. What differentiates this system from earlier PROFS workstations is the hardware implementation. The system uses a DEC MicroVAX II as the workstation processor and a Ramtek 9465 with two color monitors for display. A compact disk reader that can read $5\frac{1}{4}$-inch laser discs (with a storage capacity of approximately 600 megabytes) provides a convenient method for reviewing large data sets.

The POWER system was demonstrated at several national conferences including the AMS International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography and

Hydrology in Miami in January 1986. In July, SDI installed a real-time workstation at the ARTCC in Longmont, Colorado. SDI brought up the workstation software and configured the PROFS central facility (EDF) to generate and distribute, routinely, a pre-defined set of meteorological products to the workstation over a 56-kbps link. A second real-time POWER workstation was installed at NSSL for June–September to support NSSL's spring experiment and data review. SDI worked with other groups within PROFS to configure the software and install the system.

A communications study was performed by a local contractor to investigate the design options and considerations at the physical and link-level layer of a satellite broadcast communications link. The study indicates that a highly reliable simplex communications link can be established (without significantly increasing the communications bandwidth) by properly designing the link-level layer of the protocol.

During FY 1986, SDI worked closely with EFS in PROFS and the NWS Forecast Office at Denver to help develop the DAR^{3}E functional system specifications. The System Functional Specifications document was completed in March. SDI and EFS worked jointly to develop the DAR^{3}E workstation. SDI was responsible for specification of the workstation hardware, design of the software architecture, and development of most of the workstation control software. The DAR^{3}E workstation provides significant additional cabability over the workstation developed for the 1985 summer exercise: a separate workstation processor was added to provide AFOS text-handling capabilities, the image and graphics portion of the DAR^{3}E workstation was modified to include many new products and capabilities, and the user-interface was moved to a separate display device. SDI completed the integration of data acquisition, product scheduling, meteorological product generation, and product distribution software to support the DAR^{3}E workstations' need for more than 500 routinely pre-generated products (in addition to those available from AFOS). The generation of these routine products was distributed over two VAX 11/780s to provide equitable system loading and a degraded mode of operation in case of failure of either of the two processors.

SDI continued its agreement with the U.S. Air Force Space Division (SD) to provide meteorological enhancements to the Satellite Data Handling System (SDHS) and to develop and evaluate products for the Defense Meteorological Satellite Program (DMSP). In addition, SDI's role increased in FY 1986 to include helping SD plan advanced meteorological processing systems to be used in tactical locations supporting the Air Force global mission.

A working off-line SDHS Forecast Console Subsystem was installed at PROFS. The hardware and software were configured to use data tapes supplied by the Air Force Global Weather Central (AFGWC) to aid in the development and integration of new functions and capabilities. Considerable time and effort was spent developing a Barnes objective analysis scheme for integration into the SDHS operational environment at AFGWC. A study was prepared for SD and AFGWC detailing the PROFS algorithm for remapping GOES satellite data from satellite coordinates into equal-area projections such as polar stereographic and Lambert conformal. Negotiations are under way for SDI to provide the remapping algorithm to AFGWC for integration into the SDHS.

DMSP microwave temperature sounder data are routinely combined with surface pressure fields that have been calculated using a sigma-coordinate system to produce analyses of constant pressure, geostrophic winds, and vorticity at standard atmospheric pressure levels. Derived fields from these analyses are then forecast out to 24 hours by a simple barotropic prognostic model. These functions were developed to give increased diagnostic and prognostic capability to forecasters who might not have access to the normal centrally produced products and data fields. SDI is testing and evaluating the utility of these products.

SDI provided a study to SD on the uses of multispectral analysis to detect atmospheric parameters important to the Air Force tactical mission. The purpose of the study was to help the Air Force determine the suitability of a multispectral sensing capability to the DMSP polar-orbiting platform.

Plans FY 1987

NWS is considering a proposal by PROFS to continue its DAR^{3}E activities for FY 1987. PROFS proposes replacing the aviation and hydrology workstations with limited-capability workstations to evaluate their functional requirements. SDI has been investigating approaches to a limited-capability workstation that retains the design philosophy and much of the software of the higher-end workstation. Other proposed developments include the integration of text and image/graphics data bases, which are now split between the AFOS and PROFS hardware.

SDI will support workstation development for the Joint Ice Center project. In particular, SDI will rework the file management function to include a commercial data-base management system.

SDI is consulting with the SD on two potential major meteorological system procurements: (1) an Integrated Weather Support System (IWSS), which would downlink vital environmental information to mobile ground units located around the globe; (2) a proposed upgrade of certain fixed-location satellite receiving and processing sites at installations around the globe. This consultation is a coordinated effort by SD which includes members of the Air Force, The Aerospace Corporation, Harris Corporation, and the Air Force Geophysics Laboratory.

Efforts to implement products being developed for the SDHS and DMSP, and to test and develop new products will continue. The Barnes analysis scheme will be integrated into the operational system at AFGWC by the end of January 1987. We envision that our GOES remapping algorithm will be modified to transform imagery from polar-orbiting satellites for implementation at AFGWC. Upon receiving final approval from SD, SDI personnel will perform two major studies: (1) Test and evaluate a number of multivariate analysis schemes primarily aimed at addressing mesoscale forecasting, as is being done at the AFGWC Severe Weather Section; (2) define processing requirements and techniques necessary to produce multispectral imagery needed to identify meteorological parameters and elements that significantly affect the Air Force mission. In addition, SDI will continue to improve the analyses of DMSP mission sensor data, and to assist SD in planning future meteorological processing systems.

FORECAST RESEARCH GROUP

The Forecast Research Group (formerly Test and Evaluation) designs and implements nowcast and forecast experiments, evaluates forecast results and nowcast improvements by use of objective quantitative analysis techniques, and prepares articles and reports for NOAA management and the open literature. The group is also responsible for developing, testing, and evaluating simple forecast models that can provide reliable forecast guidance for specific local forecast problems in the Denver WSFO area of responsibility. Particular emphasis is on the Colorado Front Range area, from the Continental Divide eastward.

Accomplishments FY 1986

The major effort was analysis of forecast results from the convective storm forecast exercise conducted by PROFS in the summer of 1985. Three independent analyses were completed: (1) analysis of forecaster accuracy in issuing severe thunderstorm and tornado warnings; (2) comparative evaluation of the performance of three hail-detection computer algorithms; and (3) analysis of short-range, local-scale probability of precipitation forecasts. Results show that the computer algorithms perform well enough to be useful as forecaster guidance in severe storm situations; the forecasters outperformed the algorithms, but not substantially. The precipitation probability forecasts show considerable skill, relative to climatology and conditional climatology, particularly for those cases when convective storms were identified in space and time by forecasters using the advanced workstation.

The three analyses included the use of conventional evaluation methods as well as a new (to meteorology) method using the statistical concepts and definitions of Signal Detection Theory. An Australian meteorologist has shown the statistical properties of Signal Detection Theory to be particularly well-suited to weather forecast evaluation. Our studies helped to highlight the advantages and limitations of the theory for evaluating severe storm forecasts.

We also developed a detailed plan for evaluating the DAR^{3}E system to be installed at the Denver WSFO starting early in FY 1987.

Finally, we worked with an ever-expanding group of meteorologists in the Boulder/Denver community to initiate a Weather Forecast Program in Boulder, using the PROFS advanced workstation capabilities. The plan is to have a daily forecast activity (Monday through Friday) involving meteorologists from local ERL laboratories, NCAR, and the Denver WSFO. The forecast activity will be extended around the clock and over weekends during interesting weather situations. The forecast activity is being designed to enhance weather forecasting research, to facilitate and encourage interaction between research and operational meteorologists, and to provide a facility for testing new forecast ideas, models, and procedures.

Plans FY 1987

- Evaluate the DAR^{3}E system installed in the Denver WSFO.
- Participate in and evaluate the new Weather Forecast Program.

WEATHER MODIFICATION PROGRAM

During a decade when the limitations to the nation's fresh water supplies are increasingly being realized, the NOAA Weather Modification Program (WMP) is taking a hard scientific look at cloud evolution and water budgets, and the realities of cloud-seeding technologies for enhancing precipitation on the meso-beta to meso-gamma scales. Research is focused on six avenues that promise breakthroughs to monitor, forecast, modify, and understand the effects of cloud systems:

- Testing and application of cloud remote sensors.
- In-cloud tracer technologies.
- Chemical/physical technologies to evaluate precipitation processes.
- Ice nucleant chemical kinetics.
- Modeling of cloud processes and their links to the mesoscale.
- Precipitation impacts on hydrology and agriculture.

The Weather Modification Program office oversees the Federal-State Cooperative Program in Weather Modification Research, which began in 1979. At that time the U.S. Congress appropriated funds for a Federal-State scientific evaluation of certain ongoing operational cloud-seeding programs. Such Federal-State cooperative programs were among the many recommendations made to the Secretary of Commerce and the President in 1978 by an independent Weather Modification Advisory Board appointed in response to the passage of Public Law 94–490, which required that the Secretary of Commerce develop a plan at the Federal level whereby weather modification research activities could be coordinated. The Board resolved that "locally controlled operational projects...offer an excellent opportunity for increasing scientific knowledge and technology development....Proper design, well-conducted operations, and careful data collection will permit useful evaluation of the effectiveness of selected multi-year operational

projects. The resulting scientific gains will be sizable, and most local users, sooner or later, will appreciate Federally-sponsored scientific evaluation of the operational projects locally supported." This resolution serves as a charter for the NOAA program.

In 1979, NOAA contracted with Colorado State University to develop a design for the conduct of the first two programs approved, the North Dakota and Utah programs; various advisory groups provided recommendations for the conduct of field research programs in these two states. In FY 1983, Nevada was added to the program. In FY 1984, Illinois was added.

Currently, research in the four states is supported through cooperative agreements with WMP. The mission of WMP is to support, conduct, and coordinate basic and applied research to understand cloud and precipitation processes and their role in the hydrologic cycle under natural influences, and with inadvertent and purposeful modification.

The summer and winter seasons and four different climate regimes are represented by the four state programs. Illinois is concerned with summer convective rain processes as they directly affect crop production in the humid, temperate climate of the Midwest cornbelt. Summer convective precipitation and hail in the sub-humid, rainfall-deficient, grain-growing regime of the northern Great Plains are the concerns of North Dakota. Utah is addressing winter orographic snowfall and its impact on summer runoff and irrigated agriculture in the arid to semi-arid climate of the Great Basin, which is precipitation-deficient in all seasons. Initial cloud-seeding activities in Nevada were stimulated by requests from Native Americans who were concerned about the amount of water reaching their reservations. To assure water supplies for irrigated agriculture and urban uses, Nevada must address winter precipitation on both the windward and lee sides of the Sierra Nevada where there occurs a dramatic transition from generally abundant but annually highly variable snowfall in a sub-humid climate to deficient snowfall in a semi-arid, steppe climate.

Thus each program is of regional interest, and collectively the programs are of national interest in that they address one of a very few technologies potentially available for increasing water supplies to alleviate deficit spending of the nation's fresh water. All four programs include sizable state investments.

The long-range goals of the four cooperative programs are as follows:

- Utah/NOAA: Understand the water budgets and potential for snowfall enhancement in winter orographic clouds within the Great Basin, and physically and statistically estimate the actual effects of operational seeding.

- Nevada/NOAA: Determine the effect of winter orographic cloud seeding in California on snowfall enhancement potential and water supplies in areas of Nevada downwind of the seeded target areas.

- Illinois/NOAA: Understand the feasibility of summer rainfall enhancement in the Midwest and the agriculture impacts of added rainfall during periods of water and heat stress as well as those of excessive rainfall.

- North Dakota/NOAA: Determine the potential and actual effectiveness of seeding summer convective clouds of the northern Great Plains to enhance growing-season rainfall, and determine the feasibility of hail suppression.

Accomplishments FY 1986

COOPERATIVE RESEARCH — ILLINOIS/NOAA

The Illinois State Water Survey obtained NOAA funding and formally entered the Federal-State Cooperative Research Program in April 1984. Work in earlier years, in part through other NOAA support, established the Precipitation Augmentation for Crops Experiment (PACE), which is continuing with these specific objectives:

- Determine in a scientific manner the precipitation alterations that are obtainable.
- Determine the effects of these alterations on all aspects of agriculture.
- Determine the societal and environmental desirability of these alterations.

Top priority FY–1986 activities and corresponding accomplishments were the following:

(1) Studies of cloud and precipitation elements and systems.

- Studies of convective cloud development and mergers, using existing radar echo data to define experimental units as needed in the exploratory phase of PACE, were completed.
- Satellite interpretation of precipitation systems was started. A review of the microphysics of Midwest cloud systems was completed.
- The first Illinois field studies since entry into the Cooperative program were conducted using the ISWS (Illinois State Water Survey) CHILL (CHicago and ILLinois) radar and instrumented and seeding aircraft.

(2) Studies of economic and environmental impacts of summer rain changes.

- Soil moisture was measured at four sites for studies of soilinfiltration of rainfall. New instruments for measuring soil moisture, including a neutron probe, were used.
- Research was continued to assess the agricultural economic effects of precipitation in recent wet and very dry summers and under present farm practices.

(3) Development of facilities for PACE field operations and evaluations.

- Engineering to add computer depolarization capabilities to a Doppler 10-cm radar neared completion under a special appropriation for instrumentation.
- A real-time weather satellite receiving and forecasting system was developed and used in the field.

(4) Review, interpretation, and summary of all relevant past research in the Midwest.

- Results of all past Midwest programs were reviewed, to develop scientific hypotheses and evaluation methodologies.
- A review of past ISWS cloud-motion tracer work was completed.

COOPERATIVE RESEARCH — NEVADA/NOAA

This program studies the microphysical and dynamical aspects of the problem of "area of effect" in a region of the Central Sierra Nevada where operational and research seeding programs conducted in California produce a potential for downwind effects in Nevada.

The work will continue to be focused on (1) transport, dispersion, and capture of seeding agents; (2) stable isotopes, and ice crystal growth and fallout in relation to liquid water locations in mesoscale systems; and (3) the distribution of liquid water and ice within Sierra Nevada winter storms.

Experiments continue, to demonstrate the utility of new wet-weather tracer technology. The oxygen isotope ratio in snow (180/160), which is established when water substance freezes in a cloud, is providing a means to estimate where in a cloud and by what growth processes (vapor deposition or accretion) snow crystals gather their mass. Silver sampling in snow is demonstrating the confinement of ground-released particles (AgI) and is showing what portions of cloud volumes are reached by particle plumes in clouds

over complex terrain. The use of two compositions of particles with similar size and mass distributions, one active and one inactive as ice nucleants, is being developed to distinguish between cloud nucleation and scavenging processes; a third season of field testing added data points that actually show this difference and began to confirm (1) the validity of the dual-tracer hypothesis and (2) the participation of the ice nucleant in the precipitation-forming process.

Under a special grant for instrumentation, Nevada built an improved, mobile dual-wavelength radiometer for continuous monitoring of atmospheric water vapor and cloud liquid water.

COOPERATIVE RESEARCH — NORTH DAKOTA/NOAA

In FY 1986, analyses of available airborne tracer data on transport and dispersion in cumulus clouds were largely completed, and the airborne applications of two recently developed analyzers for SF_6 to investigations of cloud top mixing and ice activation were more thoroughly investigated. A vigorous mixing region was observed near the top of small cumuli utilizing mid-cloud releases of SF_6, located and sensed by these analyzers. Cumuli are found to have preferred regions of mixing, and uniform dispersion throughout cloud volume is more likely to be late than early in cloud life cycles.

A plume of AgI cloud seeding agent and SF_6 was used to investigate the activation and growth of ice particles in a stratocumulus cloud which was deliberately overseeded. The results suggest that the growth of ice was limited by vapor diffusion into the seeding plume, and that under these conditions of competition for vapor, about half of the seeding agent had produced detectable ice particles 17.5 min after treatment.

Radar studies were also conducted to relate cloud echo height and volume to rain volume, using data from a narrow-beam radar provided by the Bureau of Reclamation, which improved the resolution of the measurements.

Results of field tests of fast-acting ice crystal nucleants developed for North Dakota in the Colorado State University Atmospheric Simulation Laboratory led to improved hypotheses on the kinetics and effects of saturation on nucleation rate. Generator modification is needed for efficient burning, but use of ice crystals as nuclei is potentially a major breakthrough for timing treatment and precipitation growth in rapidly evolving cumulus clouds.

COOPERATIVE RESEARCH — UTAH/NOAA

The three major research challenges to the Utah/NOAA program are (1) to determine the spatial and temporal distribution and evolution of supercooled cloud water, (2) to evaluate the effectiveness of delivery of seeding materials, and (3) to determine the trajectories of natural and seeded cloud and precipitation particles.

FY 1986 was a year devoted to intensive analyses of an outstanding set of physical measurements that provide a strong basis for evaluating the cloud water budget and will contribute substantially to the refinement of the operational technology and total assessment of the snowpack enhancement program. The measurements were derived from a very successful experiment in January and February of 1985, during which studies of windflow and cloud processes were emphasized, using, simultaneously, a dual-wavelength radiometer to measure liquid water content, a K-band radar to detect the conversion of liquid water to ice crystals and measure cloud top height, a polarized lidar to follow cloud base height and phase of water, a C-band (5 cm) Doppler radar to determine low-level wind fields up and along the barrier, constant-level balloons and SF_6 released to track airflow and plumes, and supporting soundings, timing sensors, and precipitation gauges. Numerous publications will present results that link mesoscale and cloud-scale processes.

Plans FY 1987

COOPERATIVE RESEARCH — ILLINOIS/NOAA

FY 1987 will be the third full year of Illinois participation in the program. Analyses of radar echo evolution and cloud microphysics measured by aircraft based on data acquired in the FY–1986 field study will start. Satellite cloud studies will be integrated with the radar studies to identify cloud/echo types most likely to be suitable for increased precipitation efficiency, and thus for further cloud physics studies by remote sensing and aircraft. These studies will provide insights on characteristics of clouds during the third driest summer in recorded Illinois history. The Illinois State Water Survey will complete modification of its HOT (Hydrometeorological Operational Tool) 10-cm radar to include a polarization capability, which, with its existing CHILL 10-cm radar (a national facility), will provide a dual-Doppler radar capability with polarization. Use of soil moisture measurements and economic models will be continued, to assess major effects of real or hypothetical precipitation variations on agriculture production capacity and water quality. A second field study of summer convective clouds in Illinois is planned.

COOPERATIVE RESEARCH — NEVADA/NOAA

A field program during the winter and spring of 1987 will continue to assist in (1) development of tracer technologies and studies of the spatial and temporal dispersion of seeding aerosols; (2) studies of the temperature range over which the water has frozen to form the ice crystals and snowflakes reaching the surface in the project area; (3) assessment of nucleation, scavenging, and precipitation processes using chemical and isotope techniques; (4) determination of the precipitation, supercooled liquid water, and ice across the Sierra Nevada crest, using a surface network that includes radars and a microwave radiometer; and (5) determination of the chemical makeup of the snow falling downwind of the Sierra Nevada crest. Field tests will be conducted for a dual-wavelength radiometer developed in FY 1986 for shared use in the Federal-State program.

COOPERATIVE RESEARCH — NORTH DAKOTA/NOAA

Following are the principal activities for FY 1987:

- Wrap-up analyses of the pioneering 1984 and 1985 preliminary tracer studies of cloud transport and correlated cloud physics to determine plume and treatment characteristics over time and space.

- Laboratory tests to improve reliability and efficiency of cloud seeding generators that produce the new fast-acting ice crystal nucleants, such as the chemical complex AgIAgCl NaCl.

- Continuation of a comparative exploratory field experiment on in-cloud diffusion and treatment signatures for relatively fast- and slow-reacting AgI chemical complexes.

- Continued 2–D modeling of the theorized North Dakota precipitation process.

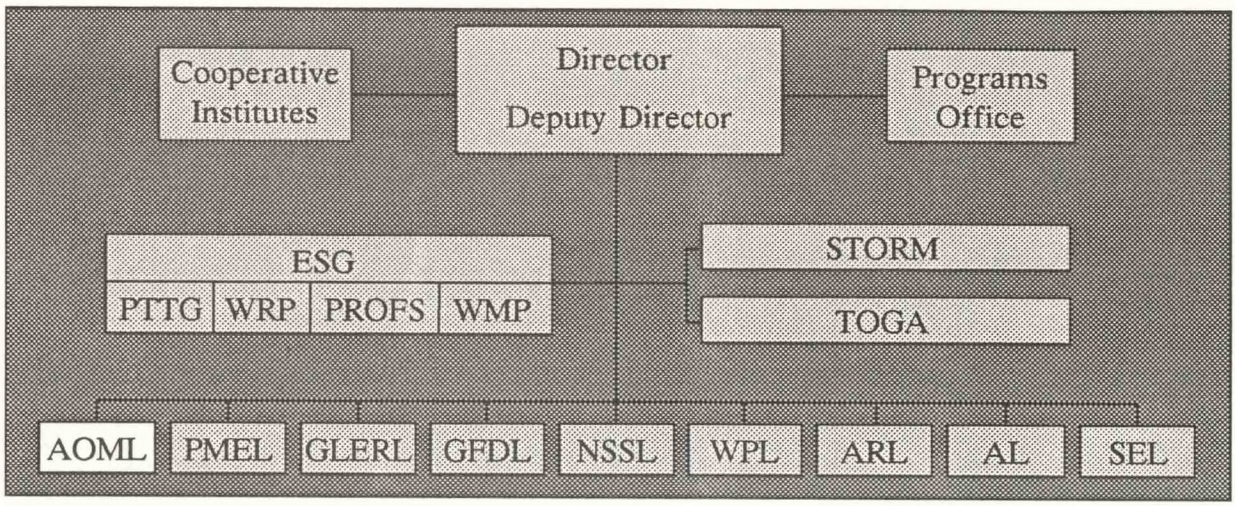
- Further analyses of radar data to complement the existing climatology of cloud echo volumes vs. rainfall, and to determine the time between first and maximum echo heights for treated and untreated cells; and initial field studies to attempt to relate cloud transport and microphysics to first echo.

- Implementation of a GOES weather satellite receiving and weather analysis system, with field tests in 1987, as provided by a special appropriation for instrumentation.

- Initiation of studies and modeling of convergence fields to improve forecasts of convective cloud activity.

COOPERATIVE RESEARCH — UTAH/NOAA

FY–1987 activities will focus on continued intensive analyses of the valuable and comprehensive data sets from the 1985 field study of orographic clouds in the Tushar mountains. These analyses of cloud motions, liquid water development, and precipitation processes will address case studies and the overall season. Limited field work focused on tracer studies of plume transport and delivery of seeding material may be undertaken as well.



ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORY

Miami, Florida

Hugo F. Bezdek, Director

The Atlantic Oceanographic and Meteorological Laboratory (AOML) is organized to pursue basic and applied research programs in oceanography and tropical meteorology. Oceanographic investigations center on fluxes of energy, momentum, and materials through the air-sea interface; the transport and composition (thermal and chemical) of water in the ocean volume; and hydrothermal processes of mineralization at seafloor-spreading centers. Meteorological research is carried out to improve the description, understanding, and prediction of hurricanes. The research program is enlarged by the Cooperative Institute for Marine and Atmospheric Studies (CIMAS), a joint enterprise with the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. CIMAS enables NOAA and university scientists to collaborate on problems of mutual interest, and facilitates the participation of visiting scientists. AOML's current research program concerns processes relating to climate, weather observation and prediction, marine observation and prediction, marine resources, and air quality.

CLIMATE RESEARCH

Climate research at AOML focuses on aspects of ocean heat transport and storage in relation to interannual and longer term variations of weather and climate. AOML activities in these areas are part of the NOAA contribution to national and international programs for climate research. Contributions to the international program on the Tropical Oceans and Global Atmosphere (TOGA) are a major program area, and plans are in progress for structuring other activities so as to take maximum advantage of the World Ocean Circulation Experiment (WOCE), which is expected to be a major national and international activity during the remainder of the century.

The scope of problems being addressed requires extensive cooperation and coordination between groups. Tradition and convenient access to sea-going research facilities result in a research program with emphasis on collection and analysis of oceanographic data. The ultimate goal of the work is to

improve forecasting of oceanic and atmospheric variations using predictive models. Model development per se is not a major part of the climate research program at AOML, but focus is provided by the data needs of models, model-data interaction, and observations for parameterization of physical processes in models and for evaluation of models.

Accomplishments FY 1986

TROPICAL OCEAN CLIMATE STUDIES

Tropical ocean climate studies at AOML consist of participation in the continuing NOAA Equatorial Pacific Ocean Climate Studies (EPOCS) program, analysis and interpretation of tropical ocean data collected during the First GARP Global Experiment (FGGE) of 1979, and beginning work in connection with the international program Tropical Oceans and Global Atmosphere (TOGA), which has objectives very similar to those of EPOCS, but which concerns all the tropical oceans rather than just the equatorial Pacific Ocean. The common focus of this work is to describe, understand, and predict the large-scale air-sea interaction processes associated with the major mode of interannual large-scale climate variation—the El Niño/Southern Oscillation (ENSO) phenomenon. AOML scientists contributed to knowledge of this phenomenon both through observations and through developments in skill of modeling.

Development of new low-cost, satellite-tracked drifting buoys made possible a large increase in the number of drifting buoys deployed to monitor sea surface temperatures in the tropical oceans. In addition to a substantial increase in the number of drifters being operated in the eastern Pacific, an initial deployment of seven drifters was made in the western Pacific in cooperation with scientists of the People's Republic of China who are partcipating in TOGA. An initial deployment of 20 buoys was made also in the Arabian Sea and Bay of Bengal regions of the Indian Ocean.

Data from the drifting buoys operated over several years were used to calculate the average upwelling velocity and its seasonal modulation in the near-equatorial region of the eastern Pacific. The average upwelling velocity obtained agrees very well with that given by the GFDL ocean circulation model, and the seasonal variations reflect the annual and semiannual variations of surface wind.

The existing drifter data base was used to evaluate statistics of surface currents in the eastern tropical Pacific. Preliminary results from this study indicate that the cost of data collection can be reduced by as much as two-thirds by programming the buoys to limited transmission. These statistics also provide the first estimate of such characteristics as the integral time scale and turbulent dispersivity of surface currents in the tropical Pacific.

In the drifter data, evidence was found of energetic mesoscale current variability in the North Equatorial Current. Intense winter winds passing through orographic gaps cause locally intense upwelling on the Pacific coast of Central America. The resulting thermocline anomalies and currents then propagate westward into the North Pacific, evidently governed by Rossby wave dynamics.

Two research cruises were conducted to investigate the hydrography and currents in a region of the tropical Pacific farther south than heretofore has been studied in EPOCS. Historical data suggest that in "canonical" El Niño events positive sea-surface temperature and surface wind anomalies appear earliest in the region, then propagate northward along the coast and westward along the Equator. During the last decade, research on El Niño phenomena has focused primarily upon the nature of the equatorial propagation. The anomalies associated with El Niño are much broader than the so-called equatorial wave guide, however. The study of hydrography and currents of the southeast tropical Pacific expands EPOCS work into these off-equatorial aspects. Initial results indicate that on the large scale, conditions were quite similar to those observed in the same seasons during the middle 1960s. The new and better observing tools now available made possible the observation of mesoscale features with Rossby wave characteristics. They have previously been observed close to the coast of South America, but never before so far offshore, and their origin is not yet known.

In January 1984 we started to develop a quasi-real-time XBT data base for use in initializing and evaluating the GFDL ocean circulation model. The data base will be used in cooperation with the NWS Climate Analysis Center (CAC) for producing basin-wide subsurface temperature fields and monitoring variables associated with El Niño. Real-time data from Global Telecommunication System (GTS) dissemination, and from cooperative observing programs between AOML and several Latin American institutions, and delayed data from the TOGA data center at Scripps Institution of Oceanography are used in this data base. In FY 1986 experiments began on initialization of the model (using the data base) and on use of the model to generate diagnostic products.

Because oceanographic observations are relatively sparse, a methodology is needed for assimilating them into models in a continuous fashion. Of two variational methods considered, one was selected for further development as a data assimilation strategy. A relatively simple ocean circulation model, the AOML Data Assimilation Model (ADAM), was written to provide an efficient vehicle for development and evaluation of the data assimilation strategy before applying it to more realistic (but also more demanding of computer resources) models such as the GFDL ocean circulation model.

Plans were completed and preparations began for using altimeter data from GEOSAT to observe sea level and geostrophic currents in the eastern tropical Pacific. Although data from this satellite are not optimal for the task, they provide an opportunity to begin work with what is expected to be the premier new oceanographic data collection system of the 1990s.

A computational study is under way to determine the feasibility of using the techniques of ocean acoustic tomography to monitor and study ENSO phenomena. Sound speed profiles were constructed from the CTD data obtained during the 18 EPOCS cruises that took place between June 1981 and December 1985. The two sections considered lie along the Equator from 85°W to 145°W and along 85°W from 5°N to 5°S. An empirical orthogonal function analysis of these profiles has provided representations of the annual signal and the 1982–83 ENSO perturbation in terms of a few simple functions of depth, horizontal range (latitude or longitude, depending on the section), and time. The annual signal was found to be a significant contributor to the sound-speed field and cannot be ignored when sound propagation is modeled.

By using computer models of sound transmission, with these sound-speed data as input, it was found that propagation conditions fundamentally change during an ENSO event within a layer of the ocean extending from a depth of a few tens of meters to a few hundred meters, the precise dimensions depending on the local bathymetry. Ray paths that turn over in this layer of instability during a normal period of time are able to travel on to great distances. During an ENSO event, however, the temperature anomalies bend these same ray paths in such a way that they strike the bottom before traveling very far and thereby experience the usual severe losses in intensity. This change in propagation conditions prevents the straightforward application of tomography to studies of ocean dynamics in the layer. It was determined, however, that a short-range acoustic remote-sensing system can be used to monitor changes in the ocean within the layer.

SUBTROPICAL ATLANTIC CLIMATE STUDIES

Analyses of data collected in the Straits of Florida continue to increase our understanding of the dynamics of this western boundary current. Current meter data show the most energetic meandering motion at 5 days and 12 days with wavelengths of 210 km and 340 km, respectively. These meanders propagate downstream (northward) with phase speeds of 28–36 km day^{-1}. They account for almost 25% of the subinertial energy after removal of longer period variability. Dynamically, there is no strong correlation between these motions and local winds, suggestive of propagation from further upstream in the Caribbean-Gulf region. There is, however, significant correlation between local wind stress and volume transport at periods of 3–4 days and 20 days. These transport variations are predominantly barotropic.

Computing barotropic and baroclinic energy conversion terms suggests that the flow is stable for either type of variability. Large velocity variances on the eastern side of the Florida Straits have been related to interaction of the Florida Current with the Bahamian Bank.

Real-time monitoring of the Florida Current transport continues. Submarine cable observations of the transport have been collected continuously since early 1982. Longer time series of transport from coastal tide gauge stations are also available. Comparisons of pre-STACS (Subtropical Atlantic Climate Studies) direct transport observations with tide gauge data suggest correlations similar to those found between transport and tidal height in the STACS data, but somewhat degraded. The degradation is apparently related to smaller errors in the STACS direct measurements.

The western boundary sections at Abaco and Mayaguana Islands, the Bahamas, and San Juan, Puerto Rico were occupied during January, March, and July 1986. Conductivity, temperature, and depth (CTD), current profiler, and nutrient measurements were taken along these sections to continue the time series begun in April 1985. Four current meter moorings were deployed along the Abaco section during the March cruise. The moorings will be recovered during a March 1987 cruise. The resulting data will provide continuous observations of the velocity and temperature field along this section. For the first time, Freon observations were taken during the July 1986 cruise.

The direct current measurements collected along the Abaco section show considerable high-frequency (less than seasonal) variability in total section transport. There is no obvious seasonal signal in these observations, in contrast to the large seasonal signal found in a wind-driven numerical model of the North Atlantic. The model portrays a seasonally reversing subtropical gyre with maximum northward boundary flow of $13 \times 10^6\ m^3\ s^{-1}$ during March. The flow reverses in November with a southward boundary flow of $13 \times 10^6\ m^3\ s^{-1}$. The observations show similar amplitude in transport variability but no similarity in phase. In fact, large southward flow was observed in April.

Observations show considerable variability in the intensity of the deep equatorward flow at the Abaco section. Freon and temperature observations obtained in July 1986 suggest two regimes of equatorward flow at the Abaco, Mayaguana, and Puerto Rico sections. One is located on the continental slope between 1000 m and 3000 m; the other is farther offshore at somewhat greater depths. The Freon observations indicate that this tracer can provide more information along the western boundary than is available from salinity and oxygen distributions.

Plans FY 1987

TROPICAL OCEAN CLIMATE STUDIES

The main focus of these studies will continue to be on the objectives of the EPOCS and TOGA programs. Continuing close association with GFDL and NWS/CAC is planned for development and use of models.

A substantial fleet of satellite-tracked drifting buoys will be maintained in the eastern tropical Pacific Ocean, and a smaller number of buoys will be deployed in the Indian and western Pacific Oceans. Several interpretive studies, including determination of Lagrangian statistics and their implications for observational requirements, and description of eddies induced by coastal wind events will be completed. Interpretive studies will begin on the new drifting-buoy data sets from the Indian and western Pacific Oceans, the latter in conjunction with colleagues from the People's Republic of China.

Two research vessel cruises will be conducted to investigate further the hydrography and currents in the southeast tropical Pacific. On the second of these cruises, in cooperation with scientists of PMEL, we will investigate a transoceanic hydrographic section at 15°S in the Pacific Ocean. This section is one of several recommended by the U.S. WOCE Planning Report No. 2 to be observed during the decade of the 1980s. Interpretive reports of the oceanographic conditions in the southeast tropical Pacific and the 15°S section will be completed in late 1987.

Intensive work will continue, in cooperation with NWS/CAC, on use of the GFDL ocean circulation model for diagnosis of oceanographic events observed during the El Niño event of 1982–83 and subsequently, and for producing oceanographic data products of general interest. Work on data assimilation in models is intended to facilitate these applications. The AOML data-assimilating model will be put on the CYBER 205 at Gaithersburg for rapid evaluation of the data assimilation strategy being considered; if the results are positive, work can begin on incorporating the strategy into the more elaborate model.

If GEOSAT is put into a repeating orbit and the altimeter data are released for civilian use in early FY 1987, as planned, ancillary oceanographic data will be collected, and analysis of the combined data set will begin.

The feasibility of ocean acoustic tomography in the equatorial Pacific will continue to be investigated through a joint program with the Propagation Studies Group of WPL. Two efforts will be undertaken. First, it will be determined if it is possible to monitor an ENSO event by measuring the level of sound in the layer of instability: either the ambient noise that is always present in the ocean or sound from a source placed in the ocean as part of the monitoring system. Second, it will be determined if it is possible to use middle-depth rays, i.e., those rays that turn over below the layer of instability, as the basis for an ocean acoustic tomography experiment.

SUBTROPICAL ATLANTIC CLIMATE STUDIES

Continued analysis of the Florida Current data is planned, to elucidate further the causes of variability and its role in the North Atlantic circulation. Florida Current variability will be compared with variability observed previously at 26°N, 29°N, off Cape Hatteras, and east of the Bahamas. In particular, any seasonal signals at these locations will be compared with each other and with results from a wind-driven model of the North Atlantic. These comparisons will be used for model verification and to indicate where additional observations are required.

Monitoring of Florida Current transport by submarine cable and tide gauges will continue. Data will be provided to other interested investigators.

The nutrient, geostrophic velocity, and direct velocity observations along the Abaco, Mayaguana, and Puerto Rico sections will be combined to obtain a representation of the total flow field and water mass distributions at these locations. Variability in the flow field and water masses will be determined to study forcing of the western boundary currents and sources of transport. Transport through sections occupied across an entrance to the Windward Passage and across the Caribbean Sea will be estimated to determine the relative contribution to Florida Current transport of flow through these sections. Results from previous studies are inconclusive relative to these contributions.

Three cruises are scheduled for FY 1987 (October–November 1986 and March and September 1987) to continue time series along the sections described above. A minimum 2-year time series is planned. Additional sections are to be added off Barbuda and Barbados in an attempt to determine the continuity of the deep equatorward flow to the south. Direct velocity, CTD, nutrient, and Freon data are to be collected. In addition, the current meters retrieved off Abaco will be redeployed between Trinidad and Barbados. Correlations of transport through this passage with Florida Current transport will be attempted, to determine if the latter transport is related to other than North Atlantic winds. Numerical model-observational comparisons will provide the framework for analysis of the data.

WEATHER OBSERVATION AND PREDICTION

AOML is NOAA's primary focus for research in tropical meteorology and hurricanes. Research teams concentrate on field programs, numerical hurricane modeling, and theoretical studies of hurricanes. The Laboratory's hurricane field program makes use of NOAA research aircraft to acquire unique data sets. AOML interacts with the National Hurricane Center (NHC) and the National Mete-

orological Center (NMC) in problems of hurricane prediction, with the National Center for Atmospheric Research (NCAR) on scientific investigations of the inner cores of hurricanes, and with GFDL on hurricane modeling.

Accomplishments FY 1986

SYNOPTIC-SCALE FLOW AROUND MATURE HURRICANES

This work is designed to investigate steering currents and their effects on mature hurricanes. Data are obtained from Omega dropwindsondes (ODWs) deployed from NOAA P-3 aircraft. Accuracy of the ODW winds was improved in 1986 by implementation of two new algorithms—a turn removal technique, and a phase-smoothing routine. Flight tracks for the synoptic flow experiment were modified in 1985 to include airborne Doppler radar wind data within 75 km of the center of the hurricane. The new tracks were tested in Hurricane Gloria (1985). Analysis of the resulting data indicates that it will be necessary to obtain higher density ODW data near future storm centers. The flight tracks were, therefore, again redesigned and are scheduled for retesting during the 1987 hurricane season.

MESOSCALE PRECIPITATION FEATURES IN MATURE HURRICANES

The purpose of this research is to identify the mesoscale and convective-scale features in mature hurricanes and to describe their basic organization and structure. The major effort in FY 1986 was an eyewall water budget study conducted in Hurricane Norbert on 24–25 September 1984. The data collected (microphysics, flight-level, radar reflectivity, and Doppler radar velocities) are sufficient to make a reasonable estimate of the eyewall water budget, but will not allow an estimate of the water transport outside the eyewall region. This limitation will be remedied in future experiments by expanding the analysis domain. Analysis of a supercell event in Hurricane Norbert on 22 September 1984 started. The Norbert data are unique in that airborne Doppler radar data are available to describe the wind field within the supercell.

CONVECTIVE RAINBANDS IN HURRICANES

On 8 October 1985, a two-aircraft rainband experiment was carried out in Tropical Storm Isabel. Soundings were obtained by aircraft ascent and descent and by dropwindsonde on the interior and exterior sides of a convectively active (relative to the storm's eye) rainband. Penetrations of the rainband were made with a low-level aircraft. Flight-level data, radar-reflectivity data, and Doppler radar data were obtained.

VORTEX MOTION AND DYNAMICS

This work seeks to obtain improved understanding of hurricane motion, evolution, and internal structure through detailed analysis of data from research aircraft and through formulation of relatively simple quasi-analytical models. Data from several hurricanes in 1983, 1984, and 1985 offer substantial confirmation of the Hurricane Research Division's convective ring model (published in 1982) of cyclic changes in storm intensity and eye size. Formulation and testing of a newer, separate quasi-analytical model for the motion of a specified hurricane-like barotropic vortex showed significant progress. Results indicate that earlier studies of vortex motion on a beta-plane, which predicted a westward drift of such a vortex due to the beta-effect, may be incorrect.

MICROPHYSICAL STUDIES IN HURRICANES

The goal of this research is to determine the microphysical characteristics of hurricane clouds as a function of the measured vertical velocity of the air at meaningful structural locations within the storm,

to understand how the latent heat released on the cloud scale is transmitted to the mesoscale circulation of the storm.

Regions of high (greater than 30 dBZ) radar reflectivity above the 0°C isotherm were positively correlated with both strong updrafts and the presence of liquid precipitation. Strong radial gradients of radar reflectivity in the outer edge of the eyewall were often associated with downdrafts and high concentrations of ice particles.

Analysis of the 24 September 1984 microphysical data from an eyewall water budget study in Hurricane Norbert showed a large number of branched particles on the northwest side of the storm. Columns were found in many parts of the outer stratiform regions of the west and south sides of the storm. No liquid water was observed after the first two penetrations of the eyewall.

CONVECTIVE AND MESOSCALE STRUCTURE OF LANDFALLING HURRICANES

The purpose of this research is to study changes in hurricane structure as revealed by land-based radar data recorded from NWS radars during the landfall of hurricanes. The time variation of the area-averaged rainfall in the inner core regions of Hurricanes Alicia and David was estimated from land-based radar data. The estimates were made before landfall when the inner core regions of the hurricanes were over the ocean. During the time of the calculations, Alicia had an eyewall but David did not. Rainfall was calculated for the area within 75 km of the center of the hurricanes. The area-averaged rainfall varied by a factor of 3 over a period of about 2–3 h. Rainfall variations of this magnitude were calculated for both the inner rainbands and the eyewall region of Hurricane Alicia. These variations were caused by small mesoscale areas of convection that formed, matured, and dissipated during the 2–3 h time frame.

OBSERVATIONAL STUDIES OF HURRICANE AIR-SEA INTERACTION

An ocean response experiment was conducted in Hurricane Gloria on 26 September 1985. Fifteen airborne expendable current probes (AXCPs) and mini-drifting buoys were successfully dropped from the NOAA research aircraft. Preliminary analysis of AXCP data sets from Gloria and Norbert were completed. The patterns in Gloria and Norbert were similar, showing maximum mixed-layer currents in the right-rear quadrant where sea-surface temperature decreases were largest (about -2°C).

A second 1985 experiment obtained boundary layer wind profiles in the hurricane force winds of Gloria over the cold water of the Gulf of Maine. The near-surface winds were found to be less than 50% of the 45 m s^{-1} cloud base winds. Over warm water, the wind reduction between cloud base and the sea surface is usually only about 80%.

We developed new methods for real-time estimation of surface winds using the University of Massachusetts airborne stepped-frequency microwave radiometer (SFMR).

QUASI-SPECTRAL HURRICANE MODEL

To achieve substantial improvement over the existing operational hurricane prediction models and to facilitate studies of hurricane dynamics, a general-purpose hurricane model on nested grids is under development. This model uses an accurate and flexible numerical method known as QSTING (Quasi-Spectral Time Integration on Nested Grids) in which the spectral representation of field variables is by cubic B-splines. This model combines the numerical accuracy of spectral methods with the freedom of specifying boundary/interface conditions for nested finite domains.

Inertial instability in the hurricane outflow layer was studied with the QSTING model in an attempt to explain the formation of outflow jets. The outflow layer was represented by a "shallow water" layer on an f-plane. The finest model resolution was 10 km in a 240 km^2 domain and the model was nested to the sixth level by an expansion factor of 2, so that the outermost domain was 7,680 km^2. The outflow layer was initialized with a geostrophically balanced parallel flow. To represent the forcing from below by a hurricane, source terms of mass and angular momentum were specified.

The outflow patterns that developed depended quite sensitively on the specified environment flow. If no motion was initially assumed in the environment, and if the source terms were axially asymmetric, the resulting spiral outflow, cyclonic near the source and turning anticyclonic about 250 km from the center, remained axisymmetric and there was no sign of unstable breakdown into asymmetry in spite of the development of a ring of negative absolute vorticity just outside the radius of directional turning. However, when a sheared flow was assumed for the environment, the outflow was channeled into two well-defined branches in opposite directions, stretching more than 800 km from the source region. The outflow developed in distinctly different patterns depending on whether the environment shear was cyclonic or anticyclonic.

The primary cause of the outflow jet formation was found to be the interaction of the forced mass outflow with the large-scale environmental shear. Inertial instability was not directly involved.

HURRICANE-TRACK FORECAST ERRORS

The goal of this work is to improve the barotropic hurricane-track forecast model (SANBAR) which is used operationally at NHC. We improved the large-scale deep-layer mean (DLM) analysis technique used to initialize SANBAR, and also changed the numerics. The revised model is known as SAN85. Test cases from the 1979–1982 hurricane seasons showed that the average forecast errors (AFEs) for SAN85 were 10–20% better than AFEs for the CLIPER (climatology/ persistence) model out to 48 hours, usually equal or better than the AFEs for the NHC73 (statistical/dynamic) model out to 72 hours, and better than the AFEs for the MFM (movable fine mesh) model out to 36 hours. SAN85 will be used operationally in 1986.

Work with ODW data collected in hurricanes indicates that the SAN85 initial analysis provides inadequate resolution of the ODW information. The forecasts for Debby (1982) were rerun using initial data from a spline-based objective analysis that provided better resolution of a trough and cutoff low in the vicinity of the storm. This resulted in greatly reduced forecast errors. Subsequent modifications to the SAN85 scan analyses slightly improved the resolution. This reduced the forecast errors for the ODW cases by 10–20% for the 36–72 h forecast intervals.

The 1985 hurricane season provided more than 20 additional cases with which to test the ability of the wind data derived from the VISSR Atmospheric Sounder (VAS) to resolve the DLM environmental flow field in the vicinity of a hurricane. The 1985 cases were combined with archived cases from the 1982 and 1983 hurricane seasons. Although the sample size is still too small to establish any statistical significance, the satellite-derived wind (SDW) data in a majority of cases produced a reduction in the forecast errors when used in the SAN85 model. On a homogeneous sample, the AFEs for SAN85 with SDW were 10–40% better than AFEs for CLIPER at 12–72 h, and 15–20% better than AFEs for SAN85 without SDW (except at 12 h). The SAN85 (SDW) forecasts were comparable with the MFM results out to 72 h. The SAN85 with SDW will be made available to the forecasters operationally during the 1986 season.

OBJECTIVE TROPICAL WIND ANALYSIS

Twice-daily analyses of low-level and 200-mb winds over the tropical Atlantic region, archived by the National Hurricane Center, were used to diagnose the structure of synoptic-scale disturbances in the 3–5 day period. The work was concentrated on July 1985 during which a series of strong disturbances propagated through the region. These disturbances were found to have a preferred westward shift of the 200-mb trough relative to the low-level trough of somewhat less than one-quarter cycle. The disturbances were related to systems later detected in the Eastern Pacific. The vorticity propagation characteristics showed that advection by the mean wind has the major role at lower levels. At 200 mb, however, the meridional advection of mean vorticity is more important.

Rawinsonde data from several island stations were used to resolve the vertical structure of the disturbances. The kinetic energy at the lower and upper levels was found to be about equal. The

systems propagate westward faster than the mean wind at any level but the zonal phase speed is relatively constant with height. This is probably a result of vertical coupling by cumulus convection.

Research on the long-term variability of the Atlantic tropical winds started. Monthly mean winds were derived for June through November 1975–1985 and will be used to develop a climatological atlas. Empirical Orthogonal Functions were derived to extract the dominant intra- and inter-annual variability from the wind data.

OBJECTIVE ANALYSIS OF THE HURRICANE ENVIRONMENT

The goal is to develop for the large-scale environment of hurricanes an objective analysis scheme that incorporates ODW and other available data such as rawinsonde data, NOAA P–3 and Air Force reconnaissance data, commercial aircraft data, and satellite data. The effect of data initialization on hurricane track prediction models will also be studied.

We completed a quasi-three-dimensional set of winds for Hurricane Debby (1982) at 50-mb intervals from 100 mb to the surface. Data input came from ODWs, Caribbean and U.S. rawinsondes, NOAA P–3 and Air Force reconnaissance aircraft, surface ships, commercial aircraft, Univ. of Wisconsin satellite-derived products, and NMC operational analyses. The raw data were carefully edited to promote consistency between the data sources before input to the analysis package. An iterative scheme was used to couple the horizontal analyses vertically by creating bogus data where the analyzed fields are noisy. A nested grid provided increased horizontal resolution near the hurricane.

In a preliminary test, the wind fields for Debby were used to initialize the SANBAR model and a 72-h prediction was made. The predicted storm tracks were considerably better than forecasts made from other initial analyses.

Plans FY 1987

SYNOPTIC-SCALE FLOW AROUND MATURE HURRICANES

A cooperative research program was formalized with NMC to determine the effect of ODW data on NMC's dynamical hurricane track models. NMC agreed to continue testing the MFM hurricane track model with and without ODW data and to initialize the MFM with the RAFS (Regional Analysis and Forecast System) analysis to provide higher resolution in the initial conditions than does the global analysis that is currently used to initialize the MFM.

MESOSCALE PRECIPITATION FEATURES IN MATURE HURRICANES

The water budget of the eyewall in Hurricane Norbert on 24–25 September 1984 will be completed. A similar analysis of the water budget in Hurricane Norbert on 22 September, stressing the differences in storm structure and water transport, will start. Analysis of the supercell event in Norbert will continue.

CONVECTIVE RAINBANDS IN HURRICANES

Analyses of rainbands in Hurricane Raymond (1983) and Tropical Storm Isabel (1985) will continue. The thermodynamic modification of boundary layer air by the surface outflow associated with convective downdrafts within the rainband will be examined using thermodynamic data obtained during low-level aircraft passes, and an analysis of the recovery of the boundary layer air as it flows from the rainband toward the eyewall is planned.

VORTEX MOTION AND DYNAMICS

The confirmatory concentric-eyewall observations will be prepared for formal publication. The theoretical barotropic vortex-motion work will be completed, and the model will be extended to include baroclinic and nonlinear effects.

MICROPHYSICAL STUDIES IN HURRICANES

Analysis of the available melting-layer data for hurricanes will be completed. Data from Hurricane Norbert will be used to study the origins of ice in hurricane clouds. Electric field data will be collected in one or more hurricanes.

CONVECTIVE AND MESOSCALE STRUCTURE OF LANDFALLING HURRICANES

Work on the convective and mesoscale structure of Hurricanes David, Frederic, and Alicia will be documented. A color video tape, which will include radar data of the landfall of Hurricanes David, Frederic, Alicia, Diana, and Elena, will be made and distributed to the coastal offices of NWS and other interested organizations.

OBSERVATIONAL STUDIES OF HURRICANE AIR-SEA INTERACTION

We plan to install an improved version of the SFMR on the NOAA aircraft during the 1986 hurricane seasons and to continue testing algorithms for real-time calculations of surface winds. Analysis of boundary layer observations made in Gloria, Isadore, and Josephine will continue.

QUASI-SPECTRAL HURRICANE MODEL

Work on the hurricane outflow layer will continue into early FY 1987. A theoretical plan has been worked out for implementing a mesh-moving capability. Remaining work, however, will require considerable time for programming and testing. When the mesh-moving capability is ready, the first physical application will be the barotropic prediction of a hurricane vortex. If initial tests are satisfactory, prediction experiments with real data may be initiated.

HURRICANE-TRACK FORECAST ERRORS

Work to test the effect of ODW data on the analyses and forecasts will continue. The operational SAN85 forecasts with SDW from the 1986 season will be verified and compared with the SAN85 forecasts without the SDW data.

OBJECTIVE TROPICAL WIND ANALYSIS

The relationship of the variability of the monthly mean winds to climatic fluctuations, such as the El Niño/Southern Oscillation, and hurricane cycles will be studied. Work on a wind atlas will start. Spectra of the winds for 1981–1985 will be derived and used in the design of filters to isolate the variability in the 10–20 day monsoonal period and the 30–60 day global oscillation period. Objective techniques will be used to investigate the wind variability in these bands and its relationship to hurricane cycles.

OBJECTIVE ANALYSIS OF THE HURRICANE ENVIRONMENT

New flight-track patterns designed to increase data coverage near the storm center were flown successfully in Hurricane Gloria (1985). The results will be analyzed to assess the degree to which airborne Doppler radar data taken inside the vortex core can be matched to the ODW observations in the larger-scale environment. A quasi-three-dimensional temperature analysis for Debby will be completed, and an analysis of Debby's relative humidity field will be started. Further investigations using the Debby analysis in a barotropic prediction model will be carried out.

AIR QUALITY

Air quality research at AOML has two foci. One is to develop an understanding of the geochemical cycles (sources, sinks, and transformation processes) and distributions (horizontal and vertical) of

major trace constituents of the atmosphere. The second is to determine what role marine biological processes have in determining the composition of the atmosphere, especially the lower troposphere, and the geochemical cycles therein. Ozone, methane, carbon monoxide, nonmethane hydrocarbon gases, and volatile organic species are measured simultaneously with studies of the upper ocean, e.g., studies of biological productivity and composition of the resident biota. In conjunction with AL, ARL, GFDL, and PMEL we hope to contribute to a diagnostic and prognostic model that assesses the effect of geochemical cycles in the lower troposphere on climate variability.

Accomplishments FY 1986

ACID RAIN

AOML was asked to examine the extent to which marine sulfur species could influence the hydrogen ion content of precipitation over land. AOML concentrated on the onshore winds from the Gulf of Mexico while PMEL studied the westerlies in the northwest. In the course of this work, methods were developed for measuring two marine sulfur intermediate species, dimethylsulfoxide and dimethylsulfone. These species are oxidation products of dimethyl sulfide, the primary marine source of volatile sulfur. Concentrations of these compounds are very significant in open ocean precipitation, but decrease to one-tenth or less only 100 miles inland. These results indicate that marine sulfur contributions to acidic precipitation over land will be important only in the immediate coastal zones, and, only when the winds are onshore. At present this contribution seems to be significant in the Pacific Northwest portion of the United States.

RADIATIVELY IMPORTANT TRACE SPECIES (RITS)

The major AOML accomplishments in the area of radiatively important trace substances were (1) documenting the complex distribution of ozone in the marine boundary layer, (2) identifying the many organic chemical species that evaporate from the sea surface and their oxidation products that affect the ozone and hydroxyl concentrations, and (3) developing and acquiring the technology and equipment to measure nonmethane hydrocarbons at sea.

We were able to confirm the existence of an apparently seasonal minimum of ozone mixing ratios in the equatorial Pacific boundary layer. Aircraft ozone profiles indicate intense stratification within the boundary layer, which in most models is assumed to be well mixed. Perhaps most intriguing is the suggestion from this research that models of a sea-surface boundary layer ozone sink may not extend to the sea-surface, but only to the top of the superadiabatic layer, i.e., about one-tenth the altitude of cloud base. Possible causes are (1) a boundary layer source of ozone (this in spite of an apparent insufficient level of key species in the ozone production cycle), or (2) a decline in intensity of an ozone sink.

Vertical profiles of the organic species over the sea surface show that very reactive compounds are totally consumed within the lower 100 m whereas more stable materials penetrate farther aloft. Oxidation products such as acetone and methanol are uniformly distributed to several hundred meters.

Plans FY 1987

ACID RAIN

Laboratory studies on the chemistry of dimethylsulfoxide and dimethylsulfone will continue, to assess their importance in the global sulfur cycle. In conjunction with an FY–1987 RITS cruise we will be investigating the processes resulting in the formation of organic acids in the boundary layer. Organic acids are major constituents determining the pH of rain over the ocean. It is very likely that the air oxidation of many of the RITS species result in significant yields of organic acids.

RADIATIVELY IMPORTANT TRACE SPECIES (RITS)

Most of the technology and equipment for detailed studies of RITS species in the remote boundary layer were in place and had been tested by the end of FY 1986. In FY 1987 we will conduct our most integrated studies of biogeochemical coupling of the RITS species in the equatorial Pacific. Experiments will be specifically designed to uncover the causes of the ozone minimum, biological or chemical, and to delineate which organic species are sources or sinks of boundary layer ozone. There is now a community-wide consensus that such an exercise is long overdue for adequate assessment of the atmospheric carbon cycle.

Finally, detailed investigations of advective processes affecting the distribution of a trace chemical species such as ozone will be conducted during an aircraft experiment in the western Pacific and eastern Indian Oceans. The experiments will include direct measurements of ozone fluxes by collaborating academic investigators and our own measurements of meteorological parameters and key species in the global cycle of ozone, such as carbon monoxide and methane.

MARINE RESOURCES

AOML studies in Marine Resources are directed toward determining the chemical and thermal effects on the ocean of hydrothermal venting at the ocean floor from representative sections of the slow-spreading Gorda Ridge and Mid-Atlantic Ridge. These efforts are central to the objectives of the NOAA VENTS program.

AOML, in cooperation with the National Marine Fisheries Service (NMFS), has been conducting research with the long-term goal of understanding environmental controls on commercial fisheries.

Accomplishments FY 1986

VENTS

Gorda Ridge

The discovery of active hydrothermal venting on the northern Gorda Ridge by the NOAA VENTS program in 1985 was followed up in June 1986 by a cruise of the NOAA Ship *Discoverer*, which involved collaboration between scientists from NOAA AOML, PMEL, and Oregon State University. The cruise accomplished several objectives:

- Measurement of water column properties indicated that the venting has continued at about the same intensity as in 1985.
- By using a combination of methods to measure physical and chemical indicators of venting in the water column, and by using deep-towed camera-temperature instrumentation to record properties of the seafloor and near-bottom water, the zone of venting was determined to be within an area 2 km wide by 4 km long.
- Analysis of suspended particulate matter samples revealed water-borne particles with mineral compositions indicative of hydrothermal activity (anhydrite and nontronite).
- Bathymetric and magnetic profiles were taken across the rift valley at and away from the hydrothermal site; the profiles are being analyzed to infer characteristics of hydrothermal circulation and to obtain a basis for comparison with hydrothermal sites on the Mid-Atlantic Ridge.

- Six targets were identified as potential venting zones for submersible investigation in a follow-up operation with the Navy submersible *Sea Cliff* and the U.S. Geological Survey R/V *S.P. Lee*. The highest priority target identified is a row of hills constructed of fractured pillow flows.

- The follow-up operation in August 1986 with the *Sea Cliff* and the *S.P. Lee* involved collaboration between NOAA, USGS, Oregon State University, and University of California scientists. It investigated hydrothermal venting sites on the northern and southern Gorda Ridge and further delimited the hydrothermal venting site on the northern Gorda Ridge site (GR–14).

Mid-Atlantic Ridge

The first direct observations of black-smoker-type geysers in the Atlantic Ocean were made by a team of NOAA, Woods Hole Oceanographic Institution, and Massachusetts Institute of Technology scientists with the submersible *Alvin*, as part of a dive series on a cruise of R/V *Atlantis II* between 16 May and 18 June 1986. The work was supported by NOAA and the National Science Foundation. The black smokers observed from the submersible are the first to be found outside the Pacific Ocean. They had been discovered by a NOAA research cruise in 1985 at a water depth of 3650 m in the rift valley of the Mid-Atlantic Ridge, near latitude 26°N, longitude 45°W, known as the Trans-Atlantic Geotraverse (TAG) Hydrothermal Field. The seafloor is spreading to both sides of the Mid-Atlantic Ridge more slowly (about 2.5 cm per year) than the submerged volcanic mountain ranges of the Pacific Ocean are spreading (up to 25 cm per year). The recent discovery of the black smokers in the Atlantic Ocean and the direct observations suggest that such seafloor geysers have a significant role in the Atlantic Ocean and Indian Ocean, as well as the Pacific Ocean, in cooling the Earth, controlling the chemical composition of the oceans, concentrating metallic mineral deposits, and supporting the chemosynthetic adaptation of living organisms.

Specific results of the dives are summarized as follows:

- Direct observations and sampling revealed that the rocks exposed on the mound are primarily polymetallic massive sulfides. The size and shape of the deposit (estimated 4.5 million metric tons), which is still growing, are similar to many economically important mineral deposits on land that may have originally formed under similar conditions on the seafloor.

- A sequence of hot springs was encountered, from shimmering water, to geysers discharging white smoke, to black smokers, as fluid temperatures increased from the edge to the center of the mound. A smoker venting blue-white smoke was observed for the first time. A group of black smokers situated at the center of the mound vented such a large, dense black cloud of metal particles that visibility from the submersible was partially obscured.

- Hot-water samples were recovered and temperatures were measured to determine the effect of the venting on the composition and temperature of the ocean.

- Swarms of thousands of eyeless shrimps representing a new genus were observed and sampled around the black smokers. They are hypothesized to be living representatives of *Paleodictyon nodosum*, a fossil preserved in sedimentary rocks that were deposited on the seafloor between 70 and 320 million years ago.

- The observations made on the dives demonstrate that black smokers at this site on the Mid-Atlantic Ridge are venting at least as intensely as their counterparts in the Pacific Ocean. Such black smokers will probably be found at many other sites on slow-spreading oceanic ridges in the Atlantic Ocean and western Indian Ocean where they may have a significant effect on the ocean environment, the concentration of seafloor mineral deposits, and the adaptation of living organisms.

Significant progress was also made in both water column and bottom sediment research on the Mid-Atlantic Ridge. Relative to the water column a strong quantifiable, statistically significant (corr. coef. = 0.88) relationship was demonstrated between the optical signal of a nephelometer and total reactive manganese (TRM), the classic tracer of hydrothermal plumes. This relationship was demonstrated to be valid for TRM concentrations ranging from background up to those encountered within tens of meters from black smokers. As such, a reliable real-time in situ tracer of hydrothermal plumes is available to guide VENTS-related work. Recovery of a 1.3-m core composed of nearly pure hydrothermal material adjacent to the black smokers at the TAG site on the Mid-Atlantic Ridge has provided the program with the most complete and sedimentologically unique hydrothermal core yet taken from the Mid-Atlantic Ridge. The time history of this highly metalliferous core has revealed variations in metal concentrations, mineralogy, and sediment input. Relative to the last, this core contains two turbidite units composed of metalliferous sediment debris; they are the first metalliferous turbidites recovered from any hydrothermal area. The mineralogy of the metalliferous sediments includes discrete grains of ore minerals such as bornite. Rare-earth element analysis of selected sediment samples was initiated to determine the genesis of the hydrothermal component. The ongoing and nearly completed work on the core will provide a unique chronology over a period of at least 10^4 years of variations in hydrothermal activity at a representative site on a slow-spreading oceanic ridge.

FISHERIES OCEANOGRAPHY COOPERATIVE INVESTIGATIONS (FOCI)

For the past several years, AOML has been conducting research in cooperation with NMFS, with the long-term goal of understanding direct and indirect environmental controls on the year class strength of commercial fisheries. Initial work in this area was conducted under the Long-Range Environmental Effects Research Program (L–RERP)and was focused on the northern Gulf of Mexico. This work detailed the relationship between larval fish growth and abundance and the concentration or dilution of their planktonic food resource by physical processes. Starting in FY 1986 the focus of this effort was moved to the pollock spawning area in the Shelikof Strait where a cooperative research effort is conducted by PMEL, NWAFC, and AOML.

At the same time, preparatory to field work extending to new areas and fish species, a project was initiated through CIMAS to improve sampling technology and sample processing. For the first time, zooplankton data were gathered by traditional, acoustic, and optical means in conjunction with continuous acoustic records of current shear. A similar sampling effort was then carried out with NMFS/NWAFC personnel in the Shelikof Straits during May 1986. The cruise was scheduled to coincide with maximum abundances of larval pollock. Technical advances made it possible for us to collect data that will for the first time establish the vertical distribution of pollock larvae and their food, and the degree to which biological patch size is related to horizontal gradients in vertical current shear.

Plans FY 1987

VENTS

AOML personnel will devote their efforts to the determination of heat and mass transfer and geologic controls of venting at representative sites on the slow-spreading Gorda Ridge and Mid-Atlantic Ridge. The work involves analysis of the results of two cruises (NOAA Ship *Discoverer* and USGS R/V *S.P. Lee*) on the Gorda Ridge, submersible dives (*Alvin*) on the Mid-Atlantic Ridge, and organization and leadership of a follow-up cruise to locate venting zones of the northern Gorda Ridge and to characterize the effluents at these zones. With guidance provided by the results of the prior Gorda Ridge cruises a bottom-sampling program will be undertaken in the vicinity of station GR–14 with the intention of recovering and evaluating bottom sediment to determine the quantitative and qualitative hydrothermal input and the variation of this input through time. In addition, data workup from prior

VENTS cruises in both the Atlantic and Pacific will continue. Rare-earth-element, transition-element, and major-element analyses of definitive sediment samples will be completed, interpreted, and prepared for publication.

FISHERIES OCEANOGRAPHY COOPERATIVE INVESTIGATIONS (FOCI)

Data analysis will occupy most of FY 1987. Processing of the physical and photographic data is well under way, and we anticipate presenting initial results in collaboration with NMFS/NWAFC at the winter AGU/ASLO meeting. Analysis of plankton results awaits sorting and sampling being conducted in Poland. On the basis of our impressions of the data at hand we have tentatively scheduled a cruise with NMFS/NWAFC in April 1987 during the pollock spawning period. The objective of that cruise would be to understand the factors controlling the distribution and concentration of pollock eggs.

MARINE OBSERVATION AND PREDICTION

AOML research in Marine Observation and Prediction is concentrated in the following areas: (1) Improving the definition and measurement of the ocean bottom depth for charting, navigation, and bathymetric purposes. (2) Potential operational system evaluation and demonstrations. This research is aimed at improving the observational equipment and techniques used to collect data on the marine environment; particular emphasis is placed on the use of new, advanced, high-technology systems. (3) Improving measurements of naturally occurring water column particulate distributions and the distribution of particulates produced through human activities (e.g., dumping in the ocean).

Accomplishments FY 1986

ECHO FORMATION MODELS

The AOML bottom-echo-formation model was refined and further developed. When provided with a set of input parameters characterizing a bottom environment, the model will produce the echo signal to be expected from such a bottom. An experiment conducted in August 1986 in Chesapeake Bay provided field data for model evaluation.

OPERATIONAL SYSTEM EVALUATION

A joint effort by AOML, NWS, USCG, National Ocean Survey, and Codar Systems, Inc. was made to establish an operational demonstration of CODAR (Coastal Ocean Dynamics Applications Radar) in the Straits of Florida. By late summer the two remote sites, Fisher Island (Miami) and Port Everglades (Fort Lauderdale), were transmitting radial components of the sea-surface currents to the central site at AOML. The central site computer combines the radial components into a total vector map every 3 hours, and plots the values as located vectors that show speed and direction every 4 km within a triangular shaped area of approximatedly 1500 km^2. Maps are plotted at the scale of NOAA Nautical Chart 11460 so that users such as the USCG can simply overlay the current vectors for their specific needs. The maps are being circulated among marine interests for comment.

FLORIDA ATLANTIC COAST TRANSPORT STUDY (FACTS)

FACTS as a program was completed in FY 1986. AOML produced lengthy reports on Lagrangian drifter studies and on inverted echo sounder/pressure gauge (IES/PG) studies. The drifter study showed evidence of Gulf Stream influence on the coastal zone between Palm Beach and Jacksonville, and documented that flotsam and jetsam could come ashore on the Florida Atlantic coast both north and south of Cape Canaveral. IES/PG studies showed the need for further development in instrumen-

tation design, and led to a proposal to develop an acoustic altimeter in advance of the Topographic Experiment (TOPEX) satellite mission, for which IES/PGs are planned as in situ verification devices. FACTS results will be published in FY 1987.

Plans FY 1987

ECHO FORMATION MODELS

The development of the bottom-echo-formation model will continue. The data gathered in the Chesapeake Bay experiment will be analyzed. Data were gathered on different bottom types, permitting a comparison of model echo shape predictions with echo shapes measured in the field experiment.

BOTTOM-INTERACTING ACOUSTICS

Plans are in progress for a joint research program with the Institute of Acoustics, Academia Sinica, People's Republic of China, to develop ocean acoustic remote-sensing techniques for determining sea-bottom parameters in the coastal zone. The program will consist of two related but distinct components: (1) development of an inversion technique for determining bottom backscattering strength and bottom reflectivity at low grazing angles from knowledge of the range dependence and vertical coherence of reverberation; and (2) development of an inversion technique for determining the frequency and depth dependence of the sea-bed acoustic attenuation coefficient by generalizing and synthesizing three previously developed approaches: the analysis of normal-mode waveforms, of propagation loss spectra, and of the frequency dependence of bottom reflection loss at small grazing angles.

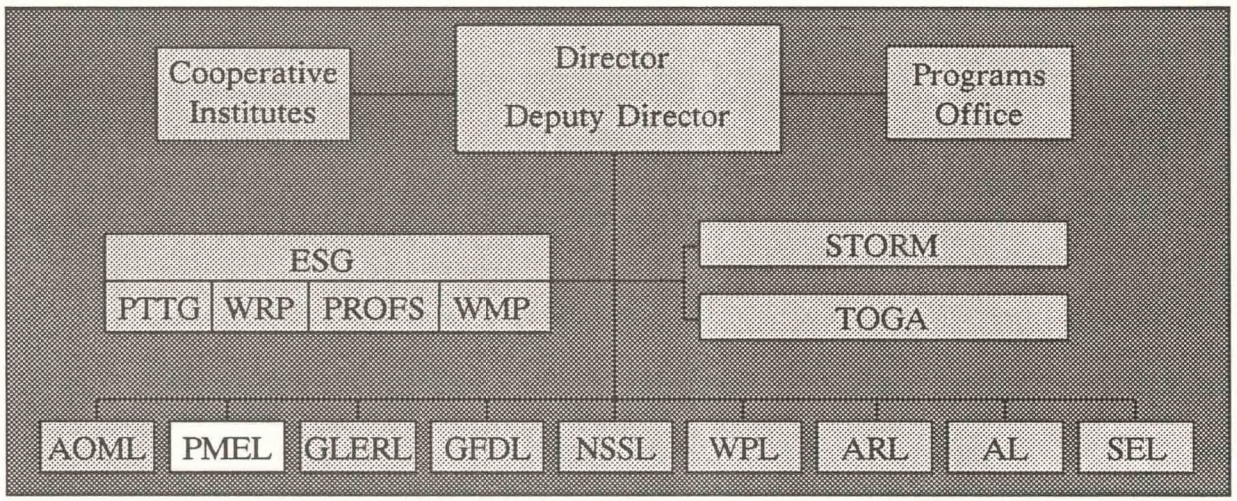
It is hoped the results obtained during the first year of the program will be the basis for a long-term relationship between NOAA and the Institute of Acoustics involving joint at-sea experiments on bottom-interacting acoustics. The ultimate goals of the work are to provide a greater understanding of the acoustic properties of the sea bottom and to help NOAA meet its survey responsibilities in the coastal zone by contributing to the improvement and expansion of technological capabilities.

OPERATIONAL SYSTEM EVALUATION

Plans for FY 1987 are centered on transferring the central CODAR site from AOML to NHC, where NWS will assume responsibility for routine operations. Users will be able to access the data in digital format through telephone dial-up to a PC; paper copies of the maps will be available by mail and/or by telecopier. AOML will conduct an independent study of the errors in determining current velocity, and will explore the ability of CODAR to return sea-state information at the entrances to Port Everglades and the Port of Miami.

OCEAN PARTICULATE DISTRIBUTIONS

Plans involving the United States and the People's Republic of China will be developed in FY 1987. An initial field experiment in particulate dispersion studies will be planned.



PACIFIC MARINE ENVIRONMENTAL LABORATORY
Seattle, Washington
Eddie N. Bernard, Director

The Pacific Marine Environmental Laboratory (PMEL) is a mission-oriented government laboratory that conducts interdisciplinary scientific investigations in oceanography, marine meteorology, and related subjects. The current PMEL programs focus on climate, marine environmental assessment, marine observation and prediction, and marine resources. Studies are conducted to improve understanding of the complex physical and geochemical processes that determine the extent of human effect on the marine environment; to define the forcing functions and the processes driving ocean circulation and the global climate system; and to improve environmental forecasting capabilities and other supporting services for marine commerce and fisheries. Products of PMEL's research are environmental information and predictive models; these are disseminated by means of scientific papers, technical reports, and presentations at scientific and public gatherings.

Two cooperative institutes, the Joint Institute for Study of the Atmosphere and Ocean (JISAO) and the Joint Institute for Marine and Atmospheric Research (JIMAR), established between NOAA and the Universities of Washington and Hawaii, respectively, provide a bridge between the academic community and PMEL scientists working in climate dynamics, environmental chemistry, tsunami propagation, and estuarine processes.

CLIMATE RESEARCH

During recent years there has been an increasing awareness of the effect of short- and long-term climatic changes on resource systems, particularly food and energy, and conversely, a concern about the effect of technology and population growth on world climate. When the National Climate Program Act was passed in 1978, NOAA became the lead agency for U.S. research in climate dynamics. PMEL scientists have been heavily involved in the formulation and implementation of the NOAA Ocean Climate Program.

To predict climatic change, it is necessary to understand the processes of heat, moisture, and momentum exchange between the ocean and atmosphere, as well as the large-scale transports of heat within the atmosphere and ocean. The ocean climate research program investigates the problem in

studies of both local (small-scale) and basin-wide (large-scale) ocean dynamics and the coupled ocean-atmosphere circulation. Laboratory participation in multi-institutional field experiments has established the groundwork for present efforts in two national climate programs: Equatorial Pacific Ocean Climate Studies (EPOCS) and Tropical Oceans and Global Atmosphere (TOGA). These studies are designed to test the hypothesis that sea-surface temperature (SST) anomalies in tropical regions have a pronounced effect on atmospheric circulation in both tropical and temperate latitudes. A major research goal is to determine the relative importance of the physical mechanisms that generate anomalies in sea-surface temperature distributions in the tropical ocean.

A crucial step in reaching that goal is to develop and validate ocean circulation models that are capable of simulating the evolution of such globally important events as El Niño. In 1985, the Tropical Modeling and Analysis Program (TMAP) was initiated at PMEL to study the mechanisms affecting tropical SST through the use of numerical modeling experiments and comparison of model results with ocean observations.

Heat transport by major western boundary currents, the Gulf Stream and the Kuroshio in the Northern Hemisphere, is also postulated to have an important effect on world climate. Western boundary current studies at PMEL continue to focus on the Florida Current as part of the Subtropical Atlantic Climate Studies (STACS).

PMEL also conducts two unique marine chemistry research programs for NOAA under the National Climate Program. These studies relate to the ocean's behavior as a sink for atmospheric carbon dioxide (CO_2), which has been steadily increasing over the past century. One project measures the flux of anthropogenic fluorocarbons into the ocean in order to trace gas diffusion across the ocean-atmosphere boundary and within the ocean. The other project examines the role of biologically produced, particulate calcium carbonate as an absorber of CO_2 at high latitudes. Together these studies will help determine the potential of the oceans for absorbing CO_2 and modifying global warming.

Accomplishments FY 1986

EQUATORIAL DYNAMICS

El Niño/Southern Oscillation (ENSO)

During certain years, large interannual changes occur in the heat content of the upper layer of the tropical Pacific. Associated with these oceanic changes (anomalies of 2–5°C in sea-surface temperature are observed) are perturbations in the atmospheric circulation that appear to initiate the ocean changes. After the near-surface heat content of the ocean is modified, further atmospheric perturbations are generated by the process of air-sea interaction. The phenomenon of mutual interaction of the tropical ocean with the global atmosphere on interannual time scales has been termed the El Niño/Southern Oscillation (ENSO) problem.

Research at PMEL on the ENSO problem is coordinated through the EPOCS program. During the past year our research program has expanded to include the western Pacific through participation in the joint U.S.–People's Republic of China program to study large-scale air-sea interaction in the western Pacific. The EPOCS field program in the eastern tropical Pacific continues. The field program encompasses deep-sea moorings that provide time series measurements of wind, air temperature, sea-surface temperature, current, and subsurface temperature; shipboard sections of temperature, salinity, and velocity along the Equator and across the major components of the circulation system; and island and coastal meteorological stations. Ship-of-opportunity temperature profile (XBT) and surface salinity data continue to be analyzed. General ocean circulation models are being used to simulate low-frequency variability in the tropical Pacific and to diagnose the causes for the variability.

Zonal variability of currents and temperatures in the eastern Pacific.

A sparse network (140°, 124°, and 110°W) of moored current meters and temperature sensors has been maintained since the spring of 1983 to measure the east-west and vertical propagation of signals along the Equator. These data were examined to assess the role of east-west advection in the momentum and heat balances. Studies of the heat balance during the early stages of the 1982–83 El Niño showed that the warming of the eastern and central Pacific was in part due to eastward advection of temperature.

It has also been documented that there is an annual spring warming of the near-surface layer during non-El Niño years. The mooring data show that this warming occurs during a period of westward flow, i.e., flow from a cold region toward a warm region, so that the spring warming cannot be related to zonal advection. Alternative causes would be changes in vertical advection or mixing or north-south advection; further studies of the field data and computer model calculations will be pursued to determine the physical processes responsible for the spring warming. Although the dynamics of spring warming appear to differ from those of the major warming of 1982–83, it does not necessarily follow that this was the case for other El Niños, because of the manifest differences between the 1982–83 event and previous events.

Eastward propagation of sea-level and water transport signals along the Equator have been documented in data sets and have been demonstrated to occur in numerical models as well. During most of 1984 and early 1985 there was a marked oscillation with a 60–70 day period in zonal current and temperature data collected at the eastern Pacific moorings. The oscillation signal propagated eastward at a speed of 2.0 m s^{-1}, which is intermediate between the estimated speeds of the first two baroclinic Kelvin wave modes. The local heating also showed a strong 60–70 day oscillation which was in quadrature with the zonal advection heating. The mechanism (atmospheric forcing or an instability) for generating the oscillation is not known at present, but it is interesting to point out that the oscillation was not observed during the 1982–83 El Niño. Because the 40–60 day waves in the atmosphere also were not well developed in the 1982–83 El Niño, the possible linkage between the 40–60 day waves and the ocean oscillation will be explored.

Thermal variability in the South Equatorial Current

A five-element array of ATLAS (Automated Temperature Line Acquisition System) moored thermistor chains was deployed along 110°W in November 1985 as part of the EPOCS study of equatorial circulation in the eastern tropical Pacific and its relation to annual and interannual SST variability. ATLAS measures air temperature, sea-surface temperature, and ten subsurface temperatures to a depth of 500 m. All data are telemetered to shore via Argos satellites. The EPOCS array along 110°W is the eastern end of a network of ATLAS moorings that has components at 165°E and 140°W as well.

Results of the South Equatorial Current (SEC) array pilot study along 110°W, which took place from June to November 1985, have been analyzed. This study used temperature measurements from ATLAS and from discrete element temperature recorder moorings at 2°N, 2°S, and 5°S, as well as subsurface temperatures measured by the equatorial current meter mooring. During the pilot study, the thermal variability was dominated by the approximately 1-month-period oscillations that occur throughout the eastern equatorial Pacific. The generally accepted explanation for these oscillations is a barotropic instability in the high shear zones of the SEC. The pressure perturbation eigenfunction for such an instability falls off rapidly south of the Equator, and dynamic height fluctuation variance at 5°S should be only a few percent of its value at 2°N. However, the observations indicated nearly equal variances at 2°N, 2°S, and 5°S, and a slight decrease at the Equator. The observed meridional structure of the dynamic height variance was more consistent with a first-vertical-, first-meridional-mode equatorial Rossby wave. Longer records will be required to establish the statistical significance of this fit.

Variability of the North Equatorial Current

The ship-of-opportunity expendable bathythermograph (XBT) sampling program has provided a data set to be used to study the fluctuations of the zonal geostrophic currents in the tropical Pacific. Previous studies of the variability of the North Equatorial Current (Trade Wind Zone Oceanography hydrographic sections for 1964–65 and sea-level differences across the current) both indicated that there was an annual cycle in volume transport of the current with an amplitude of 6×10^6 m^3 s^{-1}.

Analysis of the XBT data, however, gave an annual amplitude of no more than 1×10^6 m^3 s^{-1}, and also showed that the southern boundary of the North Equatorial Current meandered during the year. This meander would explain an overestimate of the annual variation in the earlier studies because they both sampled between a fixed set of latitudes. The systematic errors that arise from using fixed sampling locations present a serious drawback to the use of sea-level data for estimating the transport of the North Equatorial Current.

Studies of equatorial long waves using satellite and in situ data

SST maps and imagery derived from the NOAA–6 satellite Advanced Very-High-Resolution Radiometer (AVHRR) for June and July 1981 in the eastern tropical Pacific portrayed the wave-like structure of the cool water front along the Equator from 93°W to 125°W. Absolute SST estimates from the AVHRR data agreed to within 0.6°C with shipboard data taken along 110°W between 5°N and 5°S. Cusped waves of approximately 1000 km zonal wavelength propagated west at 40 km day^{-1} phase speed; the meridional amplitudes were about 300 km. Details in the imagery showed cooler water at the cusps advecting northward and then eastward with the North Equatorial Countercurrent (NECC), consistent with the suggestion of a series of anticyclonic eddies occupying the shear zone between the NECC and the westward-flowing South Equatorial Current. The wave-like structures in the AVHRR SST maps were in agreement at the surface with an XBT temperature section made along the Equator between 93° and 125°W. This section also showed that the phase of the waves tilted westward with increasing depth over the upper 75 m. Such a phase shift, if it extended a distance 100–200 km away from the Equator, would be associated with an equatorward flux of heat. Similar phase shifts appeared in temperature time series at depths of 15 and 50 m from a mooring at 0°33'N, 110°30'W. Near-surface currents measured at this and a second mooring on the Equator at 109°40'W indicated a regular pattern of northward advection when wave cusps pass them, followed by southwest flow during the passage of wave troughs, again consistent with an equatorward flux of heat. The equatorward heat flux is also consistent with theoretical studies of the waves and the direction of surface eddy heat flux computed from drifting buoys.

Numerical Modeling

A version of the Geophysical Fluid Dynamics Laboratory (GFDL) ocean circulation model was used to perform hindcast studies of the 1982–83 El Niño event using four different wind stress fields. The history tapes for these experiments were processed at PMEL, and it was demonstrated that the differences in wind stress fields have a pronounced effect on the model-predicted SST fields. The model also indicated that zonal advection of warm water from the western equatorial Pacific to the east was the primary warming process during the initial stage of the 1982–83 event.

Real-time data acquisition in the equatorial Pacific

A real-time data acquisition system for the equatorial Pacific was implemented. It consists of moored instruments (equatorial current meter moorings and off-equatorial thermistor chain moorings) and island meteorological stations. Wind velocity, air temperature, sea-surface temperature at the moorings, and subsurface temperature at the off-equatorial moorings are being measured. The data are transmitted via satellite and through land communication lines to PMEL where they may be accessed by telephone. These data, in combination with the traditional monthly summaries published in the Climate Diagnostics Bulletin, make it possible to assess the state of the tropical Pacific and determine in near-real time whether a major climatic anomaly is developing.

WESTERN BOUNDARY CURRENTS

Measurements of the Florida Current transport continue to be derived from cross-stream voltage differences, obtained by use of an abandoned submarine cable between Settlement Point, Grand Bahama Island, and Jupiter, Florida. The cable sea-water contact was improved by cutting a small portion of the damaged cable near the cable break, to eliminate the erratic voltage offsets that have plagued the data for the last several years. A backup recording system was installed to eliminate the mandatory 3-month maintenance visits. The cross-stream voltages are now also being recorded across an active telephone cable about 20 miles to the south between West Palm Beach, Florida, and Eight Mile Rock, Grand Bahama Island. For this data set the water temperature is being recorded at both cable terminations. Preliminary results show good agreement between the West Palm Beach voltages and the Settlement Point voltages.

The seasonal cycle of the cable-measured transport for the past 4.5 years has compared well with the seasonal Florida Current transports in Anderson's model, which uses synoptic seasonal winds from the North Atlantic. The times of the spring and summer highs and the autumn low are in excellent agreement, but further work needs to be done to improve the agreement between the amplitudes of the seasonal variation, which disagree by about 25%.

Tests of Ag-AgCl electrodes in salt water showed that different electrodes have similar temperature coefficients and that individual electrodes give reproducible results. The evidence is that vertical electric field measurements in the ocean obtained with Ag-AgCl electrodes can be corrected for temperature variations. Vertical electric field recordings can then be used to determine the east-west transport. Tests are continuing on new electrodes to determine their temperature coefficient and to establish the level of drift caused by aging of the electrodes.

Geomagnetically induced voltage variations in cables can obscure the oceanographically induced signals. The separation of these two types of signals depends on recording the magnetic variations and determining, by robust least-squares methods, smooth continuous response functions. These functions can be inverted to yield the vertical distribution of electrical conductivity in the Earth, provided that the response functions are locally one dimensional. Realistic conductivity models have established the validity of the response functions and the methods used to determine them, and these methods have been applied to a unique 11-year data set of hourly values of electric and magnetic fields from Tucson, Arizona (1932–1942). The conductivity models determined from these response functions show structural details within the Earth (200–150 km) that, for the first time, compare with similar structure of the Earth determined from seismic earthquake studies.

CARBON DIOXIDE/RITS RESEARCH

For a given rate of fossil fuel combustion, the observed rate of increase in the atmospheric CO_2 burden is thought to depend primarily on the rate of ocean uptake. This oceanic influx depends in turn upon the detailed space- and time-dependent air-sea exchange of CO_2, the oceanic processes of thermocline ventilation, and the action of the marine biological "pump" by which carbon is fixed in particulate form in near-surface waters, settles, and then decomposes at depth.

Because the oceans act both as a source and a sink for atmospheric CO_2, particularly in upwelling and downwelling areas, PMEL scientists continued interdisciplinary studies of the CO_2 system in the surface and intermediate waters of the North Pacific during 1986. The purpose of these investigations was to study the dynamics of the CO_2 system along meridional transects that include major frontal systems in the North Pacific.

The distributions of Freon-11 (F–11) as a surrogate tracer were combined with precise measurements of total CO_2, total alkalinity, oxygen, nutrient, and other hydrographic data in order to estimate the amount of fossil-fuel-derived CO_2 in the surface and intermediate waters of the North Pacific. The approach uses the F–11 profiles to determine apparent vertical mixing parameters. These parameters were used in a horizontally averaged, one-dimensional vertical diffusion model along with the CO_2

source function to provide model predictions of anthropogenic CO_2 concentrations. These predictions were compared with observed estimates of excess CO_2 by using the back-calculation method and station data. The results show very good agreement between the modeled profiles and the calculated data for all stations north of the Subarctic Front. The calculations indicate that the approximately 4 × 1015 g excess carbon, or about 2% of the total estimated fossil-fuel-derived CO_2 input, now resides in the mixed layer and thermocline waters of the Subpolar Gyre.

During the CO_2/RITS (radiatively important trace species) expedition in the summer of 1986, a 135°W meridional track from 15°–60°N was reoccupied. Dramatic increases (>50%) in the thermocline burden of the F–11 transient tracers were observed, particularly at densities $\sigma_t > 26.0$. Increases of F–11 in surface waters have followed the 20% atmospheric increase during this interval.

Prototypes of two automated systems for continuous underway air/sea trace gas measurements were field tested. The first vertical profiles of a new ocean Freon tracer (F–113) were obtained.

The El Niño modulation of the sea-to-air flux of CO_2 in the eastern equatorial Pacific was measured and interpreted with respect to the global carbon cycle. Cooperative pCO_2 measurements on EPOCS and CO_2/RITS cruises continued with scientists from GMCC.

Plans FY 1987

EQUATORIAL DYNAMICS

- Acumulate all near-surface thermal data from the tropical Pacific (including Japanese fishing fleet data) to describe the seasonal cycle of temperature in the Pacific, and ultimately compare the data with model simulations of the seasonal cycle.
- Analyze the heat and momentum balances from the eastern Pacific east-west array of moorings to diagnose the causes of changes in the heat content of the near-surface layer.
- Begin a program to measure the large-scale distribution of heat content in the tropical Pacific by means of satellite-linked drifting thermistor chains.
- Continue the analysis of the 1982–83 hindcast computer modeling experiments, to understand why the near-surface currents and temperatures evolved as they did in the model calculations.
- Begin an investigation of the dynamics and predictability of simple coupled atmosphere-ocean models.
- Occupy a basin-wide deep hydrographic section along 15°S to describe the circulation of the South Pacific subtropical gyre and to estimate meridional heat and water mass transports.
- Establish the noise level of Ag-AgCl electrodes for vertical electric field measurements, to use them for recording the east-west transports from Atlas moorings.

WESTERN BOUNDARY CURRENTS

- Start modeling the variations of Florida Current, using Anderson's model and winds, to determine the origin of the event-like transport changes that occur in the Florida Current.
- Begin cross-stream voltage measurements in a coastal region to develop the engineering techniques for installing small-diameter submarine cables that could be deployed in the deep ocean to measure the transport of major ocean currents.

CARBON DIOXIDE/RITS

- Continue time-series measurements of CO_2, other greenhouse gases, and chemical tracers in the Pacific.
- Refine the prototype automated trace gas instrument for high-precision, continuous measurement of air/sea concentrations of CO_2, CH_4, and CO. Refine the prototype 16-channel data-logger system for continuous and simultaneous measurement of atmospheric and oceanographic parameters relevant to trace gas air/sea exchange and marine photochemistry.
- With GFDL, and using an ocean general circulation model, initiate basin-wide modeling studies of the evolving CO_2 and Freon thermocline distributions determined in the PMEL survey of the North Pacific, 1981–85.

MARINE ENVIRONMENTAL ASSESSMENT

Marine environmental assessment at PMEL emphasizes understanding the complex physical and geochemical processes that ultimately determine the health of the marine system and its ability to assimilate pollutants. Included are studies of suspended-sediment transport and geochemistry, distributions of hydrocarbons and synthetic organics, coastal and estuarine circulation, theoretical modeling of pollutant transport processes, and a program in marine sources of acid rain. Although the geographic focus of these studies has been Pacific Northwest and Alaskan coastal and estuarine waters, the scientific knowledge acquired and methodologies developed are applicable to other marine systems. Two major activities at PMEL are studies of the long-range fate of chronic pollutants in marine waters and oceanic precursors to acid rain.

Accomplishments FY 1986

LONG-RANGE-EFFECTS RESEARCH

In response to the Marine Protection, Research and Sanctuaries Act of 1982 and the National Ocean Pollution Research and Development and Monitoring Planning Act of 1978, PMEL has addressed environmental concerns associated with transport and marine disposal of municipal and industrial wastewater and the reaction of marine systems to continuous influx of pollutants. Under the NOAA Long-Range-Effects Research Program (L–RERP), PMEL is examining the role of suspended particulates in transporting pollutants or in removing them from the marine system. In support of these studies researchers are investigating the mechanisms by which heavy metals and organic pollutants partition between water and particulates. As these processes become better understood, we will be able to assess the long-term effect of chronic, low-level input of pollutants into the marine system.

Studies in the Puget Sound–Strait of Juan de Fuca estuarine system, under way for several years, are leading to a better understanding of the ability of estuaries to accommodate pollutant inputs. Many pollutants adhere to and move with particles, and ultimately are buried in sediments or transported out of the estuary in dissolved form. The emphasis of much PMEL research, therefore, has been particle transport and fate.

Estuarine Circulation

Research at PMEL has focused on spatial and temporal variability of transport within the estuary and exchange with the outside, both of which are important to understanding the distribution and fate

of properties including contaminants. In Puget Sound, flow is tidal with a superimposed time-varying gravitational circulation. In addition to tides, one major variation in flow occurs during deep water renewal by bottom water intrusions over the sill. These intrusions occur approximately fortnightly, but not every fortnight. During neap tides, currents on the sill are relatively weak, there is less vertical mixing, stratification increases, and a gravitational circulation intensifies in the bottom layer. Thus, relatively undiluted water from outside Admiralty Inlet is able to transit the sill, resulting in density currents that flow into the bottom of Puget Sound and propagate up-estuary, displacing existing bottom water. Prediction of the onset of intrusions is of major importance because they do not occur every fortnight. A theoretical index to predict the occurrence and intensity of intrusions based on the tidal current part of the estuarine Richardson number is being tested. Recent observations indicate that the horizontal pressure gradient across the sill drives the intrusions. The onset of several major events appeared to occur after the difference in density between inside and outside the sill reached some nominal value, and fortnightly signals also were observed in the Strait of Juan de Fuca. Estimates of the flux of water based on earlier measurements in mid-channel supported a reflux concept that some fraction of the seaward-flowing surface water was entrained into the bottom inflowing water.

Transport in the Water Column

Pollutants are derived from both natural and human sources, including riverine, atmospheric, municipal and industrial sewage discharge, and dredging operations. Mass balance calculations for many pollutants indicate that human sources exceed the natural sources, and buildup in sediments occurs over decadal or longer time scales. The assimilative capacity of an estuary is a function of the individual pollutant's physiological effects on the indigenous marine life, residence time in the estuary, biological availability and uptake, and the physical and chemical transformations occurring in the water column and in the sediments.

During 1986 PMEL scientists completed seasonal surveys of the distributions of dissolved and particulate Pb, Cu, Ni, Cd, Zn, Fe, and Mn in Puget Sound. The lowest concentrations of dissolved trace metals were found during the winter months when mixing and dilution by riverine input was highest. Pb concentrations in the near-bottom waters of the southern half of the main basin are lower than inflowing oceanic or riverine water, indicating rapid scavenging and removal by particulate matter and deposited in the underlying sediments. Other metals, including Fe, Mn, Cu, and Zn show enrichments in near-bottom waters, suggesting rapid recycling reactions at the sediment-seawater interface. The buildup of trace metals in the bottom waters is a function of remobilization rates as well as the frequency of bottom water renewal events in the Sound. During August and September of 1986 PMEL scientists conducted a 4-week study of these processes near the entrance to Admiralty Inlet. The results of this work will provide a better understanding of the effects of intrusions on the trace metal chemistry of fjord-like estuaries.

Polycyclic aromatic hydrocarbons (PAHs) are toxic hydrophobic compounds and are also generally associated with particulates. Particulate PAH concentrations in the main basin of Puget Sound decrease with depth in the water column and with distance from Seattle. The residence time of these pollutants in the water column is not sufficient for mixing to take place throughout the estuary or out of the estuary. Although these compounds are rapidly transported to the bottom sediments, resuspension and lateral transport in the bottom nepheloid layer slowly disperse these compounds throughout the fine-grained sediments of the main basin.

During the past year, PMEL also completed a multidisciplinary study of pollutant transport in the two main urbanized embayments of Puget Sound–Elliott Bay and Commencement Bay. The study demonstrated that pollutant-bearing particles were concentrated in the upper 1 m of the water column as a result of the combined riverine, atmospheric, and sewer inputs to the surface waters. Those particles that remained suspended above the pycnocline were rapidly advected out of the bay and provided a major source of polluted sediments to the main basin of Puget Sound. Particles that rapidly settle out

of the surface layer provide a significant contribution to the pollutant loading of the underlying sediments. The bottom sediments are a sink for contaminants rather than a source to the main basin.

Bottom Boundary Layer Processes

A new analytic model for steady, pressure riven flow in shallow water was developed. The model is based on a Level II turbulence closure, which assumes a local balance in the turbulence kinetic energy equation between shear production and dissipation. The results show that Level II velocity matches closely the classic log-profile over the entire water column. Satisfying a no-shear condition at the free surface, the Level II velocity is only slightly less than the log-profile at the surface. Level II velocity can be brought into agreement with the results of more sophisticated closure models in the upper part of the water column by increasing the apparent bottom roughness by a modest amount. The Level II suspended sediment concentration closely matches a modified Rouse formula over the entire water column. There is close agreement between the vertically integrated sediment flux computed from the Level II formulas and that computed from the log-velocity and modified Rouse formulas. This work provides stronger justification for these widely used formulas than previously existed.

Earlier Marine Environmental Quality work has demonstrated the importance of including time dependence in the eddy viscosity/diffusivity when modeling the tide-driven bottom boundary layer. This work is being extended to predict the vertical structure of the eddy viscosity/diffusivity and its effects on flow and sediment. The approach is to do numerical simulations using turbulence closure models. Thus far the focus has been on oscillations due to tidal motion at the M2 tidal frequency. The simulations for deep water show that at each instant the profile of eddy viscosity/diffusivity consists of a pair of undulations. The features in the profiles move upward in time because the velocity shear pattern moves upward. For a pure M2 current, the patterns of eddy viscosity/diffusivity repeat themselves twice every M2 cycle. Simulations for shallow water show that the double-peaked structure is often replaced by a single maximum at the surface, although two maxima are sometimes evident. These results bear on the near-bottom time-dependent distributions of sediment and trace metals controlled by tidal currents.

Estuarine reflux

Past theoretical work at PMEL has dealt with modeling the mean, two-layer circulation in fjords using freshwater and salt as convenient tracers to deduce the recirculation, or reflux, of water between outflowing and inflowing layers at mixing zones where fjord reaches intersect. The theory is designed to exploit historical data sets of runoff and salinity in order to deduce the circulation and reflux, and to predict the steady-state concentration of passive tracers introduced into such a system. One such historical data set is that collected in Puget Sound from 1951 to 1956. A series of hydrographic stations was revisited monthly over a 5-year period, and observations of salinity and temperature were taken at several discrete depths. To analyze the data for application of the theory we integrated them vertically over the upper and lower layers, using fits to observed current measurements as weighting functions. More than 4000 salinity observations from nearly 500 hydrographic casts at 10 sites in Puget Sound were used. Our emphasis is on the long-term circulation trends; hence the flux-weighted salinities were averaged with a 1-year running mean. Transport predictions agree reasonably well with observation, although no year-long time series of currents exist for direct comparison, especially during the mid-1950s. The flux-weighted, yearly-averaged salinity time series are being used to estimate the reflux coefficients in Puget Sound and to investigate their sensitivity to salinity and runoff variations. One bonus is that the observed salinities are frequent and stable enough to allow an analysis of the time-dependent behavior of the system over shorter, seasonal time scales. The theory is being extended to account for this and for the introduction of nonconservative tracers.

ACID RAIN RESEARCH

The surface ocean has an important role in the global biogeochemical sulfur cycle. Biogenic sulfur compounds emitted from the ocean are the dominant source of sulfate aerosol in the marine tropo-

sphere. This aerosol is a major contributor of the acid in natural precipitation and of cloud condensation nuclei. Thus marine sulfur gases may directly influence global cloud cover and hence the radiative equilibrium of the planet.

Observational studies at PMEL during the past 4 years have enabled us to quantify the flux of the dominant gaseous sulfur compound (dimethylsulfide or DMS) from the ocean to the atmosphere. The flux of DMS varies regionally and seasonally by approximately a factor of 3. Taking into account area-weighted seasonal concentrations, we calculate a net global ocean-to-atmosphere DMS flux of 0.5 Tmoles/yr (16×10^{12} g S/yr), an amount equal to roughly 20% of current anthropogenic sulfur emissions.

A coordinated oceanic-atmospheric chemistry program was initiated with the University of Washington at a remote coastal location in the northwest corner of Washington State. This makes possible an examination of gaseous DMS in the ocean and atmosphere and gaseous and particulate oxidation products of DMS in the atmosphere and the depositional flux of sulfur from the atmosphere. A new electron capture sulfur detector has been developed and is being tested; it should lower the limit of detection for gaseous sulfur compounds by 3 orders of magnitude.

Plans FY 1987

LONG-RANGE-EFFECTS RESEARCH

- Analyze the onset and propagation of intrusions with several existing data sets, which can later be assessed with the developing two-dimensional laterally averaged model.
- Analyze near-bottom observations from the FY–1986 late-summer experiment in Puget Sound and begin comparison with the bottom boundary layer model.
- Extend the theoretical study of time-dependent eddy viscosity to density intrusions superimposed on tidal currents.
- Begin year-long observations to obtain data for refining an Intrusion Index.
- Refine the channel tide model of Puget Sound and predict tidal transport and dissipation distributions.
- Continue the development of the laterally averaged, baroclinic model for the main basin of Puget Sound.
- Extend the fjord reflux theory to include time-dependent circulation and tracers.
- Complete a bathymetric data base of Puget Sound, using all available NOS digitized depth data. This will be used for a variety of computational models.
- Continue studies of trace metal recycling in the bottom boundary layer.
- Begin studies of trace metal transport by specific particle phases (i.e., fecal pellets, fecal matter, exoskeletons, etc.) in an estuary.
- Begin studies of trace metal complexation by organic ligands in estuarine systems.

ACID RAIN RESEARCH

- Develop the capability to measure trace ammonia and ammonium concentrations in seawater and the atmosphere since ammonium is the major cation affecting the acid base chemistry of the troposphere.

- Continue the coordinated oceanic-atmospheric chemistry program with the University of Washington (sulfur and nitrogen biogeochemical cycles).
- Explore the relationship of DMS flux, number of atmospheric particulates, and the biogeochemical sulfur cycle on the Earth's climate.

MARINE OBSERVATION AND PREDICTION

Marine observation and prediction research is directed toward understanding and improving the prediction of phenomena related to marine warning and forecasting services. Research subjects include sea-ice processes, vessel icing, and tsunami propagation and run-up. PMEL scientists work closely with colleagues at operational service components of NOAA such as the Navy-NOAA Joint Ice Center. Studies of sea-ice processes are also applicable to NOAA's climate research. Studies are carried out through a combination of field measurements, remote-sensing techniques, and numerical modeling.

Accomplishments FY 1986

SEA-ICE RESEARCH

The Arctic Polynya Experiment

The second phase of the Arctic Polynya Experiment (APEX) ice buoy deployment was conducted near St. Lawrence Island in the northern Bering Sea during the winter of 1986. The purpose of the buoy deployment was to study sea-ice drift in the vicinity of Bering Strait in order to provide a better basis for extending a sea-ice forecasting model to this region. The broader goals of APEX included understanding the relative effects of baroclinic currents due to brine rejection during freezing of ice in the St. Lawrence polynya, of barotropic currents due to set-up of water on the shelf by the wind, of internal ice stress due to the presence of the island, and of other forces on the motion of ice in the Bering Strait region. Data from the previous year were translated and collated, and a preliminary analysis of the sea-ice drift and the meteorological data were published.

Arctic Modeling

The sizes of wind-generated coastal polynyas have been observed to be nearly constant for steady atmospheric conditions, because of the balance between the advection of sea ice away from the coast and the area-averaged production rate of new ice. A simple model was developed to explore the relationship of several atmospheric parameters to the maximum size attained by the polynya and the speed at which the maximum is reached. The model results showed that size is strongly a function of air temperature, such that colder air produces a smaller polynya for a given offshore wind speed. However, polynya size is only moderately a function of wind speed since increasing the wind speed increases both the advection rate of ice away from shore and the ice production rate. The model results were supported by observations made during the Marginal Ice Zone Experiment (MIZEX)–West and during APEX. This has important implications for the interpretation of satellite imagery for ice-covered oceans and for understanding high-latitude climate dynamics.

The ocean circulation on the Bering and Chukchi shelves was studied using a high-resolution, barotropic numerical model. The purpose of the study was to investigate the interaction of physical processes on different spatial scales—processes such as geostrophic coastal currents, topographic control of flow, and inertial flow through straits for the geographically complex area—and to develop qualitative composites from earlier observational studies. With mean winter northerly winds and a sea-level difference of 0.45 m between the Pacific and the Arctic Oceans, the model matches the

$0.56 \times 106\ m^3\ s^{-1}$ northward water transport through Bering Strait for the 8-month winter season of 1981–1982. Westward intensification of the Bering shelf current was observed; the principal transport was from the Gulf of Anadyr, through Anadyr Strait west of St. Lawrence Island, and through Bering Strait. The balance of the transport was through Sphanberg Strait east of St. Lawrence Island but with a greater dependence on wind direction. The northward flow through Bering Strait bifurcates in the Chukchi Sea in the vicinity of Cape Lisbourne; most of the water transport heads northwest in a broad canyon, and the balance becomes the Alaska Coastal Current between Point Hope and Point Barrow. The model results provide a basis for modeling ice drift through the Bering Strait and along Alaska's west coast in winter.

Vessel Icing

Vessel icing is one of the most serious marine hazards in high-latitude waters. A set of 85 icing incidents for December 1979 to December 1983 was obtained from the radio log of WBH29, a private reporting station on Kodiak Island. Reports were verified by interviews with vessel operators and compared with NOAA weather observations. During FY 1985, an algorithm was completed that related icing to meteorological parameters. In general, rates of marine superstructure icing for vessels 20–75 m long are much worse than had been previously thought. Previous case studies included observations of vessels headed more than 120° from the wind, of vessels protected by headlands, or of vessels in only moderate weather conditions. In FY 1986, using the algorithm derived from the verified data, we developed improved nomograms for icing rates for vessels headed into or abeam of the wind for different sea temperatures and weather conditions and distributed them to mariners. The results of this work have already been incorporated by NOAA and Navy units into forecast procedures and manuals and have stimulated increased efforts to understand the physics of a broader range of icing problems in the United States and Canada.

An additional study of vessel icing showed that spray generated by a wave colliding with a ship is the only important source of water, apart from rain or snow, to the superstructure of ships during freezing events. This study used a variety of techniques to show that wind-generated spray is negligible, even in heavy seas. Wave-generated spray flux originating from a single wave collision with a ship is a function of collection efficiency, the liquid water content of the spray, the local wind speed, and the time of exposure of the ship to the spray. The vertical distribution of the liquid water content in the wave-generated spray is a function of wave height, elevation of the wave above the ship deck, and ship speed. Since rates of ice growth on vessels depend on the water flux over the decks, vessels designed for navigation in high latitudes should have minimal surface area in the foredeck and bow areas, the bow and freeboard should be reasonably high, and the hull should minimize spray generation from waves.

TSUNAMIS

The THRUST (Tsunami Hazard Reduction Using System Technology) project continued toward its goal to demonstrate the concept of a regional early warning system by coupling seismic instrumentation with state-of-the-art satellite communication technology. The design and preliminary testing of the necessary equipment were completed, and instruments were installed at Valparaiso, Chile, for a 1-year test of the system. Simulations of the local shoreline response to tsunami energy were completed, and the results will be incorporated into the early warning systems evacuation plan.

A new research effort aimed at the fundamental dynamics of tsunami generation and propagation is focusing on the Shumagin Gap region in the Aleutian Islands arc. This area has been identified as the most probable site of the next great tsunamigenic earthquake. A directional array of four bottom pressure recorders (BPRs) developed at PMEL was deployed in the open ocean near the Shumagin Gap. A complementary numerical modeling program is focused on the development of inversion techniques that will be applied to BPR records to recover the initial ocean surface displacement history at the source region.

Plans FY 1987

SEA-ICE RESEARCH

- Field work for the Beaufort and Chukchi Mesoscale Circulation Study will be conducted in August–October 1986 to deploy current meter moorings, establish a meteorological station network, and measure conductivity, temperature, and depth (CTD) in Alaska western and northern coastal waters, to understand current systems of the Chukchi and Beaufort Seas. Follow-up operations by helicopter to the ice in March–April 1987 will exchange moorings, deploy drifting ice buoys, and take winter CTD measurements.

- A joint Navy-NOAA experiment in the Chukchi and northern Bering Seas will begin in September 1987. The purpose of the program is to understand the mechanisms involved in autumn freeze-up of the Chukchi and northern Bering Seas.

- A two-dimensional, coupled ice/water model for the Bering and Chukchi shelves will be developed further in an effort to create a complete Bering-Chukchi ice-forecasting model.

TSUNAMIS

- Complete THRUST field test and document results of the THRUST program.

- Deploy a BPR at 26°N, 155°W, near the Hawaiian Islands. Assemble and test six additional BPRs to be used for continuous observations at the designated sites. Recover Shumagin Gap BPRs and deploy their replacements.

- Perform study of the background energy levels to be expected at the BPR sites, using long time series of sea level pressure available from the National Data Buoy Center. Develop software for the reduction of BPR records to directional energy information.

MARINE RESOURCES

Hydrothermal venting, which occurs along seafloor-spreading centers, represents a basic input of heat and materials into the oceans. The effect of hydrothermal venting on the marine environment is the focus of PMEL's marine resources program called VENTS. Research efforts have been specifically designed to define and quantify the chemical, geological, and physical oceanographic processes evolving from the venting of hydrothermal fluids.

The VENTS Program in FY 1986 focused on preparations for establishment of a NOAA long-term seafloor laboratory on an active hydrothermal vent field at the summit of Axial Volcano, which is located on the Juan de Fuca Ridge. Research was also conducted at the Southern Juan de Fuca site, the northern end of the Gorda Ridge, and the Mid-Atlantic Ridge, and a modest effort was carried out to assess the venting of methane along a portion of the Oregon margin.

PMEL's second major area of research in marine resources, FOCI (Fisheries-Oceanography Coordinated Investigations), began as a separately funded program in FY 1986. It is a joint effort by NOAA scientists at the Pacific Marine Environmental Laboratory (PMEL) and the Northwest and Alaska Fisheries Center (NWAFC) to address the question of the recruitment variability of commercially valuable fish and shellfish stocks in the Gulf of Alaska and Bering Sea. The long-term goal is to establish environmental indices that can be monitored and interpreted to provide useful forecasts of recruitment.

Accomplishments FY 1986

VENTS PROGRAM

Juan de Fuca Ridge

A joint NOAA and Canadian program at Axial Volcano that included the submersible *Pisces* located several submarine hydrothermal vent fields, including one that is ideal for establishing NOAA's VENTS long-term seafloor monitoring laboratory. The field was extensively mapped using an innovative in-submarine navigation system that provided mapping accuracies for the location of first-order geological features, as well as associated animal communities, to accuracies of about ± 10 m. The biological program was carried out by a Canadian research team. Special biological collections were provided to NOAA investigators. Long-term (i.e., >1 mo) moored instruments including sediment traps and current meters were deployed successfully at the vent site.

An extensive surface ship program was carried out aboard the NOAA Ship *Discoverer* in direct support of the submersible-based operations. Extensive areas of Axial Volcano were mapped using a high-resolution side-scan sonar in order to elucidate the relationship between the magma supply associated with the formation of Axial Volcano and that associated with the central portion of the Juan de Fuca spreading center. Thirteen camera tows were made within the caldera to define the extent of venting outside the main field. This work led to the discovery of active venting sites located along the east wall of the caldera.

The most significant result is that an active, well-defined vent site has been discovered and initially mapped at Axial Volcano on the central segment of the Juan de Fuca Ridge. The site contains both high- and low-temperature vents as well as a robust fauna and massive sulfides, and lies at a depth within reach of both *Alvin*- and *Pisces*-class submersibles. The site is therefore both unique and ideal for establishment of a long-term seafloor laboratory where instrumentation can be deployed to obtain long time-series data sets, which will ultimately allow quantitative modeling of hydrothermal chemical and heat inputs to the world ocean. There are no other such accessible sites along the Juan de Fuca or Gorda Ridge systems.

Investigations of the southern Juan de Fuca Ridge (SJFR) in FY 1986 focused on using measurements of the plume of hydrothermal emissions to determine the heat and particle output of an entire vent field. Comprehensive deep-tow surveys of plumes were made possible by development of SLEUTH (System for Locating Eruptive Underwater Turbidity and Hydrography), an acoustically navigated, hydrodynamically faired, CTD/transmissometer/water sampler that can be towed through near-bottom waters at 2–3 kn. A detailed deep-tow survey over the SJFR vent fields resulted in the first reported three-dimensional distribution of hydrothermal emissions. The emissions from a 10-km-long vent field formed a narrow plume elongated in the direction of the local net current and centered on the 27.70 potential density surface. The total output of conservative hydrothermal emissions was calculated from measurements of the advective transport of the plume. From these we also calculated heat flux of $5.8 \pm 2.9 \times 108$ W and dissolved manganese flux equal to 0.2 ± 0.1 mol s^{-1}.

Vent particulates from the SJFR, Axial Volcano, and Endeavour Ridge sites were studied for their chemical and mineralogical composition, and dissolution characteristics. Samples from the SJFR site were found to be the result of mixing seawater with intermediate-temperature (200°–270°C) hydrothermal fluids enriched in Fe, Si, Zn, Ba, Ca, and S. The Axial Volcano samples were characteristic of mixing reactions involving high temperature (>290°C) hydrothermal fluids and seawater.

The results of a series of field and laboratory studies indicated that for some minerals total dissolution occurs within a few hours to a few weeks of their formation. For other more stable minerals the time required for total dissolution is much longer and, therefore, individual crystals of these minerals may be expected to persist in the sediments for considerable periods of time after deposition.

Physical oceanographic studies commenced, to determine the general characteristics of the flow in and around the Juan de Fuca Ridge that can transport effluents from the various venting sites away

from the ridge and become incorporated in the general ocean circulation. Three current-meter moorings were deployed on the SJFR and 10 km east and west. CTD observations from surface to bottom were made along a line from Newport, Oregon, to the venting site and along two lines 50 km apart, extending 150 km west of the ridge and bracketing the western mooring. In addition, a mooring deployed last year 15 km west of the ridge was recovered.

Gorda Ridge

The discovery of active hydrothermal venting on the northern Gorda Ridge in 1985 was followed up in June 1986 by a cruise of the NOAA Ship *Discoverer* involving collaboration of scientists from NOAA (PMEL and AOML) and Oregon State University. The cruise accomplished three main objectives: (1) Measurement of water column properties indicated that the venting is continuing but the measured intensities appear to be somewhat weaker than in 1985; (2) the zone of venting was determined to be within an area 2 km wide by 4 km long; (3) a set of bathymetric and magnetic profiles were run across the rift valley to determine the depth of hydrothermal circulation and to provide a basis for comparison with similar data from hydrothermal sites on the Mid-Atlantic Ridge.

A follow-up operation in August 1986 with the submersible *Sea Cliff* and the R/V *S.P. Lee* involving collaboration between NOAA, USGS, Oregon State University, and University of California scientists is intended to investigate a suspected hydrothermal venting site on the northern Gorda Ridge.

Mid-Atlantic Ridge

The first direct observations of black smoker hydrothermal vents in the Atlantic Ocean were made by a team of NOAA, Woods Hole Oceanographic Institution, and Massachusetts Institute of Technology scientists with the submersible *Alvin*. These are the first to be found outside the Pacific Ocean, and this discovery of active high-temperature venting on the Mid-Atlantic ridge is strong evidence that such seafloor vents are common both in the Atlantic Ocean and Indian Ocean, as well as the Pacific Ocean. It is becoming increasingly clear that such vents are significant in cooling the Earth, in controlling the chemical composition of the oceans, in concentrating metallic mineral deposits, and as locations where unique communities of organisms congregate.

Galápagos Ridge

The alteration zone that lies below seafloor hydrothermal systems has been mapped and sampled extensively at the Galápagos Ridge extinct hydrothermal site. The altered rocks consist of shattered, friable material that has been extensively leached with respect to Na and Ca. Chemical mass balance calculations will be based on the analysis of nearby relatively unaltered basalts, the sulfides, and the alteration pipe material. In addition to mapping and sampling, magnetics and electrical resistivity experiments were carried out successfully, and the data from these experiments are being analyzed. Radioactive dating of the sulfides is being done in an attempt to determine the time interval over which the hydrothermal system was active. This study will result in the first detailed analysis of the subsurface "plumbing" system associated with a seafloor hydrothermal system.

Subduction Zones

Three days of the *Discoverer* cruise were devoted to a high-resolution side-scan sonar and photogeologic survey of the Oregon continental margin. It had previously been found that the margin exhibited the characteristic topography marked by faults along which there are active methane vent systems. These "cold" vents are apparently typical of subducting margins where relatively old crust overlain by thick accumulations of sediments is driven beneath continental boundaries. As the sediments are compressed, organically derived methane is concentrated and released to the surface, and characteristic structures (e.g., carbonate chimneys and mud volcanoes) are formed with associated unique animal communities.

The surveys revealed that there are large, active methane vents and extensive colonies of the large clams known to be associated with such active vents. If such vents are indeed characteristic of subduct-

ing margins throughout the world's ocean basins, then the volume of chemically charged fluids being released by overpressured, subducting sediments may be another significant contributor to ocean chemistry.

Technical Achievements

Capabilities for organizing and accessing SEABEAM multi-beam bathymetric data were developed that allow rapid production of color contour maps. Various gridding algorithms were investigated and an optimum set selected for use in chart generation. Several charts were produced during the year, including a complete set of ten 1:25,000 charts for Axial Volcano. New algorithms for smoothing and correcting underlying LORAN–C navigation were created; they offer a major improvement in the quality of the resulting bathymetric charts.

An automated method for displaying bottom photography data was developed that allows the photo location, orientation, exact areal field of view, bottom type, and hydrothermal indicators to be displayed on a single computer-generated color chart. A scheme for displaying color-enhanced side-scan sonar images is now operational, and development of a system for performing pattern recognition studies on side-scan sonar data began.

PMEL has recently acquired a scanning electron microscope (SEM) capable of magnifying mineral grains 10 to 300,000 times. It will be used to identify and count the minerals emitted from hydrothermal vents and in studies of dissolution and diagenesis of hydrothermal plume particulates.

FISHERIES-OCEANOGRAPHY COORDINATED INVESTIGATIONS

The initial focus of FOCI is on pollock (*theragra chalcogramma*) in the western Gulf of Alaska. Several million metric tons of these fish are caught annually, and they provide a rich source of protein at low levels of cholesterol. Use by Americans of commercial products of pollock has increased nearly twentyfold, from 6 million pounds in 1981 to 119.5 million pounds in 1985. The pollock that spawn in Shelikof Strait have been surveyed yearly since 1981 by scientists from NWAFC, and many egg and larva surveys have also been conducted. Adult fish begin to enter the Shelikof sea valley early in March and reach maximum concentration in the lower Shelikof Strait by late March. Egg concentrations are greatest in early April and are typically restricted to a region of the Strait about 50 km long and 25-km wide. This pattern of behavior makes studies of this stock tractable in time and space.

The Fishery-Oceanography Experiment (FOX) was designed to test the hypothesis that larvae and juveniles that remain in coastal waters are more likely to survive than those transported into the adjacent Alaskan Stream (oceanic waters). The critical dynamics in the physical environment are the temporal and spatial behavior of (1) wind-driven currents, (2) the Alaska Coastal Current, and (3) slope/shelf exchange.

Hydrographic data from March, July, and October 1985 were used to describe circulation and water property distributions, and their changes, in Shelikof Strait. The Alaska Coastal Current (ACC) flows toward the southwest in the upper 150 m throughout the year. The deeper water in the central part of the strait has its origin in the continental slope region to the south, and properties are a result of vertical mixing of this southern water with the overlying ACC water. Thus Shelikof Strait has an estuarine-like circulation, and the strength of the along-strait deep pressure field appears to be related to the extent of vertical mixing in the central strait. On the basis of current meter data, it is estimated that about 70% of the transport of the ACC continues along the sea valley toward the south (into the slope region) and the remainder flows along the peninsula. During particular storm events, estuarine-like flow in the bottom layer may be reversed and the entire southern portion of the sea valley flushed.

There were more storms during April 1985 than the climate average, and this appears to have resulted in colder surface water temperatures and greater mixed-layer depths than those observed in 1978, 1981, or 1986. Further, baroclinic transport in the upper 150 m was nearly 25% greater than that estimated for the other years. Preliminary analysis of zooplankton data (sorting of samples, checking, and then final quality control of results taken over a year) from 1985 indicates concentrations of

pollock larvae of the order 10^0, whereas values in 1981 were order 10^4, and shipboard estimates for 1986 were order 10^2. Evidence is mounting that our prior supposition was correct, i.e., that much of the decrease in pollock larval abundance was related to enhanced transport.

Results from the FOX aircraft research included observations in a region with high potential for storm development. The region was composed of a series of parallel rainbands. Analysis of data collected from the aircraft suggests symmetric instability as the likely mechanism for the formation and organization of the rainbands. As the area containing the rainbands approached a pre-existing polar front, a wave cyclone developed rapidly on the front. Coastal stations experienced strong winds and heavy rain squalls with the passage of the storm. The intensity of the development of this storm was underestimated by the NWS forecast models.

The objectives of two of the four ship cruises in the Shelikof Strait region were primarily acquisition of egg and larva samples and CTD data to extend existing time series. A process-oriented plankton dynamics study was conducted in May to elucidate vertical structure of pollock larvae and plankton and their relation to vertical mixing. The primary objective of the other two cruises was the deployment and recovery of current meter and pressure gauge moorings. The regional array of four moorings was deployed in October and recovered and redeployed in August. Data from this array will address questions of interannual variability and local dynamics. A four-mooring array designed to examine shelf/slope exchange processes also was deployed during the same period. One cruise was dedicated to a pilot survey of pollock spawning over the deep basin of the Bering Sea. The objective was to define the biological and physical regimes in the spawning locations as they might influence survival and transport of early life stages.

Satellite-tracked drifters were deployed in the Bering Sea and in Shelikof Strait. A drifter deployed in a spawning region over the deep basin of the Bering Sea moved quickly onto the outer shelf and has remained there, drifting slowly northwest. Nine drifters were deployed at various times and at the location of the point source of pollock eggs in Shelikof Strait. Results to date indicate that flow is bifurcated in the vicinity of the Semidi Islands, consistent with data from the moored instruments. Satellite imagery is being used to examine spatial coherence in the ACC as it leaves the confines of Shelikof Strait. All historical images and present images are being obtained. Whenever possible, the images will be used to infer surface circulation by employing recently developed analytical techniques.

Plans FY 1987

VENTS

- Prepare a highly detailed geological map of the Axial Volcano vent site that will serve as a principal reference for virtually all other data sets under investigation.

- Analyze and compare high-resolution side-scan sonar data from the Axial Volcano with direct observations of the seafloor made with deep-tow camera and submersible surveys, to establish "ground-truth" of statistically portrayed sonar reflectance. The objective is to use high-resolution sonar both as a means of monitoring within the vent site and as a reliable exploration/predictor tool for venting sites elsewhere along the ridge systems.

- Plan and execute a field observation program in 1987. This is intended to be the first year for seafloor emplacement of long-term chemical monitoring systems that are under joint development by NOAA and the University of Washington. This, and other anticipated long-term instrumentation, will require the use of a *Pisces*-class submersible under the auspices of another joint NOAA and Canadian expedition. A surface-ship program aboard the NOAA Ship *Discoverer* will again complement the submersible operations during the summer of 1987.

- Undertake a cooperative program with Oregon State University on the Oregon continental margin methane-venting sites.

- Continue studies of the chemical evolution of vented fluids and determine the vertical fluxes of vent particulates in the near-field regions of the Southern Juan de Fuca Ridge and Axial Volcano.

- Continue the dissolution studies for sulfide minerals under conditions of ambient temperature and pressure.

- Expand the physical oceanographic studies to determine the middle-depth circulation around the entire Juan de Fuca Ridge in sufficient detail to connect it to other studies of larger scale circulation in the region.

- Continue time-series plume monitoring using SLEUTH and towed CTDs in selected vent fields, to establish a data base for the detection of vent-field supply and compositional variability on a decadal time scale.

- Determine the amounts of heat and mass transfer as well as the geologic controls of venting at representative sites on the Gorda and Mid-Atlantic Ridges.

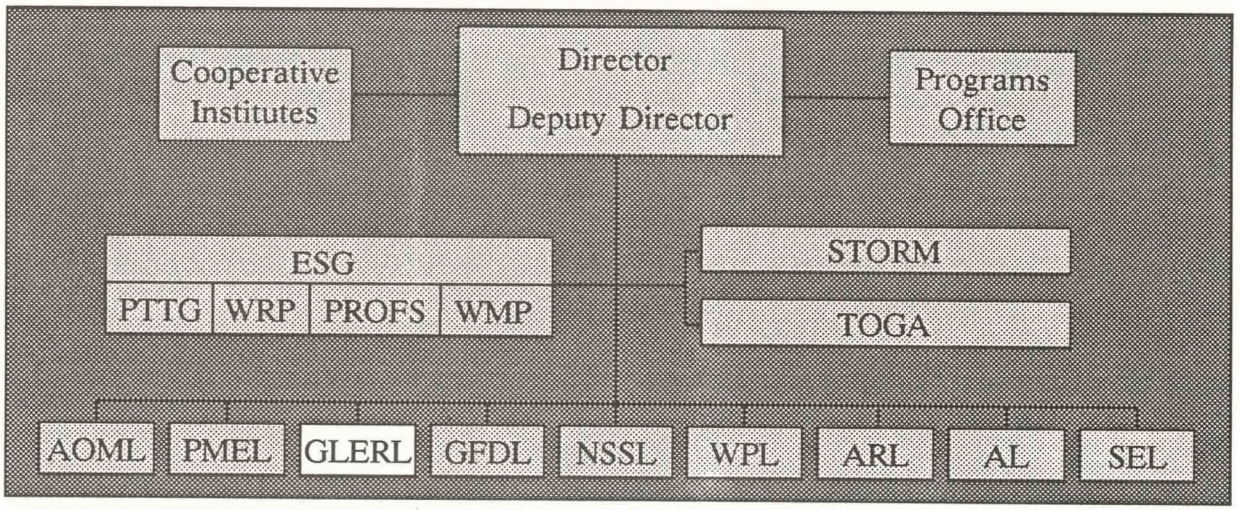
FISHERIES-OCEANOGRAPHY COORDINATED INVESTIGATIONS

- Analyze field observations from FOX 1985–1986.

- Continue acquisition of regional data (CTD measurements, egg and larva samples, currents from satellite-tracked drifters and satellite imagery, current and pressure from four moorings) to examine interannual variations.

- Deploy a fine-scale array designed to examine behavior of the ACC near the region where it bifurcates.

- Conduct meteorological observations from the NOAA P–3.



GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY
Ann Arbor, Michigan
Frank H. Quinn, Acting Director

The Great Lakes Environmental Research Laboratory (GLERL) conducts integrated, interdisciplinary environmental research in support of resource management and environmental services in coastal and estuarine waters, with special emphasis on the Great Lakes. The research program includes both basic and applied studies and combines experimental, theoretical, and empirical approaches. Field, analytical, and laboratory investigations are performed to improve understanding and prediction of environmental processes and their interdependencies with the atmosphere, land, and sediments in coastal and estuarine areas. GLERL places special emphasis on a systems approach to problem-oriented research to develop environmental service tools. Assistance is also provided to resource managers and others who wish to apply the information, tools, and services GLERL develops.

GLERL's multidisciplinary program supports the Ocean and Great Lakes Prediction Research Program of NOAA. It addresses (1) the need for new and improved simulation and prediction models of ecosystem structure and function, and of the effects of stresses and proposed remedial options, and (2) the need to assess other options while taking system dynamics and dimensions into account. Two elements of the Ocean and Great Lakes Prediction Research Program provide the focus for GLERL research: Marine Ecosystems Assessment, and Marine Hazards and Lake Hydrology.

Another major program supported by GLERL during FY 1986 was the Upper Great Lakes Connecting Channels Study, an international (U.S.-Canada) and interagency multiyear study of water quality and ecosystem dynamics in the upper Great Lakes connecting channels. The lead U.S. agency for this study is the Environmental Protection Agency (EPA), but GLERL scientists have significant roles in both the management of the project and the research conducted for it. GLERL support for this project is partially funded by EPA; the rest is provided under both the Marine Ecosystems Assessment and the Marine Hazards and Lake Hydrology elements of the Ocean and Great Lakes Prediction Research Program. For clarity, the accomplishments and plans for the Upper Great Lakes Connecting Channels Study are described separately from those for ERL programs.

MARINE ECOSYSTEMS ASSESSMENT

The Marine Ecosystems Assessment research program at GLERL is designed to (1) improve our understanding of, and predictions related to, natural marine ecosystems, physical phenomena, and the

effect of human-induced stresses on the ecosystem, and (2) help provide a sound scientific basis for management decisions pertinent to marine resources, marine pollution, and environmentally sensitive marine activities. GLERL projects include investigations into the short- and long-term effects of human, agricultural, and industrial wastes on aquatic life and water quality, particularly in the nearshore zone (the area of maximum use and conflict); the structure and function of aquatic ecosystems and the effects of human activities on those ecosystems; the measurement, analysis, and prediction of physical phenomena such as currents, river flows, and air-water-sediment interactions; and sedimentary fluxes and processes, especially sediment-contaminant interactions.

Accomplishments FY 1986

CYCLING OF TOXIC ORGANICS

Particle-Contaminant Interaction Studies

In lakes and estuaries, the adsorption of toxic organic contaminants onto particles, followed by settling and eventual burial, is commonly the major internal process controlling the residence time and concentration of these compounds in the water column. Suspended particulate matter thus plays a vital part in the contaminant geochemistry of the Great Lakes by providing a potential mechanism for cleansing the lakes through sedimentation. Understanding the interactions between different types of suspended matter and dissolved organic contaminants, and understanding the processes that affect these interactions, are critical in modeling the behavior of such contaminants in the environment.

In 1984, experiments were performed to measure the equilibrium distribution (partitioning) of a suite of contaminant organics between the dissolved, the suspended-solid, and the dissolved-organic-carbon phases. The results, primarily from a nearshore station in Lake Michigan, revealed significant seasonal changes in the partitioning between these phases. During FY 1986 similar experiments were initiated for offshore waters and will continue into FY 1987 to include the annual whiting period in the lakes. At the same time, an extensive set of new experiments was initiated in Lake Michigan to examine the rates of desorption of various trace contaminants from particulate matter. Initial results from FY 1986 show that for most of the chlorinated hydrocarbons the desorption rates are fast, but for polycyclic aromatic hydrocarbons (PAH) the rates are very slow and probably are not at steady state within the lake.

Bottom sediments and their sorbed contaminants are mixed by animal activity (bioturbation) and can be reintroduced into the water column by resuspension, especially during the winter months in the Great Lakes. GLERL has an on-going program to measure and study the fluxes of new vs. resuspended particulate matter and associated contaminants, using sediment traps moored in vertical arrays in the water column. The field portion of this research, completed in FY 1985, included the collection of more than 200 sediment samples from the traps. During FY 1986, processing and analyses of these samples were completed, and the resulting data were partially analyzed and reported to the scientific community.

In a related field program, sediment traps of different size and design used by GLERL and Canada's National Water Research Institute (NWRI) were deployed in FY 1985 in tandem arrays in the northern and southern basins of Lake Michigan to determine relative collection efficiencies over a wide range of mass fluxes. During FY 1986 these traps were retrieved, sampled, and redeployed. The field part of this experiment will continue into FY 1987. This intercomparison will be used to relate the results of GLERL's studies in Lakes Michigan, Huron, and Superior to NWRI's results in Lakes Erie and Ontario.

A coupled Lakes Model to predict the long-term response of the Great Lakes to time-dependent contaminant loads was previously developed and analyzed for sensitivity to various environmental factors. However, that model assumed a vertically homogeneous water column (i.e., not seasonally strati-

fied), and can incorporate sediment resuspension only as a rather crude approximation. In FY 1986, work began on development of a stratified, single-lake contaminant-fate model, which will explicitly incorporate sediment resuspension as a parameter and make use of the trap data.

Toxicokinetics Studies

A second and apparently important process for remobilizing contaminants out of sediments involves the direct uptake of contaminant compounds by benthic invertebrates and transfer up the food chain to higher trophic levels. GLERL's toxicokinetics program has been studying the uptake, depuration, and biotransformation rates for various toxic organics in Great Lakes invertebrates.

Previous work involving the accumulation of PAH from sediments by benthic invertebrates such as *Pontoporeia hoyi (P. hoyi)* showed that the process is complex and is affected by a number of parameters. Experimental work on the environmental factors that affect the toxicokinetics of xenobiotics in *P. hoyi* was completed. Analysis of the data indicates that organism mass is the most important physiological variable and temperature is the most important environmental variable for this organism.

Experiments were initiated this year to examine the relative sensitivity of the predominant Great Lakes benthic invertebrates, *P. hoyi* and *Mysis relicta*, to a suite of well-documented toxic organics. Pentachlorophenol, carbaryl, and DDT are commonly used as "yardsticks" for these types of studies. Pentachlorophenol and carbaryl were found to have about the same range of toxicity to both these organisms as has been observed for other amphipods. However, DDT was observed to be considerably less toxic to *P. hoyi* than has been observed for other amphipods and other crustaceans. This is possibly because *P. hoyi* have a high lipid content, and lipids store the compound, thereby making it unavailable for other reactions.

The usual measure of the toxicity of a chemical compound to a particular organism is the concentration that is lethal to 50% of the test population, known as the LC50. However, LC50 experiments do not provide any indication of what concentration level starts to produce toxic effects. GLERL developed a procedure to detect the initiation of toxicity to benthic organisms by measuring the rate of sediment reworking in a test cell under increasing concentrations of a particular toxic contaminant. Four long-term (40–50 days each) chronic toxicity tests were completed for the oligochaete worms *Limnodrilus hoffmeisteri* and *Stylodrilus heringianus*, using the pesticide endrin. Additionally, two 96-h acute LC50s were performed. From these experiments, repeatable sediment reworking rates were obtained for both species in contaminated and noncontaminated microcosms. Significant decreases in the rate of sediment reworking were found at sediment contaminant concentrations 4–5 orders of magnitude less than the LC50 value. Worm dry-weights measured after the conclusion of the experiments were also found to be a good indicator of sublethal stress and reflective of reworking rates.

Additional work done in conjunction with an outside investigator used free amino acid pools as a taxonomic tool to differentiate five species of oligochaetes. Currently, potential changes in free amino acid pools are being examined as indicators of sublethal stress in *S. heringianus*.

ECOLOGICAL SUCCESSION AND TRENDS

Ecosystem Modeling

A major problem in developing and testing the effectiveness of ecosystem models is the limited amount of comprehensive long-term data available for aquatic ecosystems, upon which model development could be based and tested. Previously, GLERL took advantage of a 20-year data base from Lake Washington (near Seattle) to develop a generic heat-diffusion model for lakes, which was then adapted for Lake Michigan. This year, the generic one-dimensional vertical heat-diffusion model, empirically parameterized in terms of the gradient Richardson number and the Brunt-Väisälä frequency, was compared with the observed vertical thermal structure and total heat content in Lake Washington for the period 1963–1976. The comparison demonstrated that the model produces a good parameterization of bulk mixing processes.

The Lake Michigan Heat-Diffusion Model was then modified and used to simulate 1985 epilimnetic thermal structure with emphasis on diel stratification. One laboratory and two field experiments were conducted during FY 1986 to assess the effect of afternoon (diel) stratification on Lake Michigan phytoplankton. Analysis of the data indicated that an important suppression of photosynthesis occurs during such afternoon stratification and that the effect may be due to ultraviolet radiation. The field and model results support the hypothesis that the wide range (very slow to fast) in epilimnetic mixing times in Lake Michigan strongly affects the fate and transport of seston and thus may also affect primary production and other light-sensitive processes.

GLERL conducted a major Lagrangian ecosystem experiment in Lake Michigan during 1983 and 1984 (Lake Michigan Ecosystem Experiment) to define and quantify biological and chemical processes causing dynamic short-term and seasonal ecological changes in Lake Michigan phytoplankton. During FY 1986 the data from that field experiment were used to complete and calibrate a long-term total-phosphorus model for Lake Michigan. The total-phosphorus simulations from the model compare well with observed values, and simulations of annual spring phytoplankton bloom conditions generally reproduce observations. A related model that simulates Lake Michigan's summer pelagic food web (phosphorus, phytoplankton, zooplankton, planktivorous fish) was also constructed and calibrated against the concentrations and process rates observed during the Lake Michigan Ecosystem Experiment. The model was used to explore the hypothesis that Lake Michigan's summer food-web structure is sometimes controlled by fish dynamics.

Ecosystem Dynamics

Ecosystem dynamics involves the determination and study of the critical first-order processes that control the flow of nutrients and energy through the ecosystem and determine the composition and pattern of succession of biota in the lakes. GLERL has an established program to examine and evaluate the importance of various temporal and spatial aspects of the Great Lakes ecosystem.

Significant progress was made toward completing analyses of the data from the Lake Michigan Ecosystem Experiment. Comparisons of epilimnetic nutrient depletion rates with primary production and sinking rates were completed, and evaluations of the spatial and temporal variations of nine nutrients, temperature, and drifter movement during 1983 and 1984 were about 80% completed.

Seasonal studies of Lake Michigan phytoplankton previously documented long-term changes in both surface and deep phytoplankton communities. Surface-water population changes were attributed to food web modification resulting from a large decline in alewife populations. In FY 1986 it was shown that recent changes in the fish communities have cascaded to affect the deep chlorophyll layer as well.

Bacteria are an often ignored part of marine ecosystems. Yet previous studies have shown that bacterial production may account for a significant part of the total production in the Great Lakes. Thus, a more detailed knowledge of bacterial dynamics is necessary to quantify and understand the transfer of food and energy through the Great Lakes ecosystem. Analyses of the results of bacteria field experiments conducted in FY 1985 were completed and preliminary findings were confirmed in FY 1986. Bacterial populations in the Great Lakes exhibited a decrease in activity and abundance with depth, a consistent seasonal pattern of production (increasing until the onset of stratification and slowly decreasing thereafter), and reasonable balance of growth and grazing rates except during the period when bacteria abundance increased (June). Experiments to study the kinetics of the removal of low levels of primary amines by bacteria were completed. The results confirmed that although bacterial growth rates appear to be controlled by the amount of labile organic substrate available, grazing is a major factor in controlling bacterial abundance, and therefore total population uptake activity.

GLERL scientists continued to use the new Microcinematography Laboratory established last year. A previous study of the feeding mechanism employed by a major species of Great Lakes copepods, *Diaptomus spp.*, revealed that a significant number of algal cells escaped even though they had been drawn within easy capture range of the copepod. This observation led to FY–1986 experiments to examine the effects of algal morphology as a defense mechanism against capture. Traditional feeding

experiments were combined with high-speed microcinematographic studies. Information from these experiments is being processed and should provide us with a better understanding of zooplankton/phytoplankton interactions, leading toward better predictions of seasonal plankton succession.

Winter Under-Ice Ecology Pilot Study

Information on the population dynamics of organisms living under the ice during winters in the Great Lakes is scant. Studies in other parts of the world show that significant biological activity can be present under marine ice. GLERL initiated a pilot study in FY 1986 to evaluate the importance of under-ice ecology in the Great Lakes. Field projects involving winter phytoplankton sampling in Grand Traverse Bay and Lake Huron were initiated. Studies are under way to examine the physiological state of phytoplankton from both sampling areas.

A pre-ice cruise in late January and a trip on the ice in early March were made to determine how well copepods winter-over in ice-covered Grand Traverse Bay, a 190-m-deep fjord-like bay on Lake Michigan. Photosynthetically active radiation transmittance through various types of ice occurring in the bay was determined. An ice thickness time and space series was collected and will be used to analyze ice dynamics and radiation transmittance. Before ice cover, phytoplankton concentration and zooplankton feeding rates were low, as expected. Under ice cover, a bloom of phytoplankton and high zooplankton feeding rates were observed. These preliminary results suggest that ice may enhance survival and production of zooplankton.

Benthic samples were collected along a depth transect in Grand Traverse Bay through the ice cover in March and again in April after the ice had melted. Preliminary inspection of March samples indicated that Grand Traverse Bay possesses a rich and diverse macroinvertebrate community in the winter.

FOOD WEB DYNAMICS AND PELAGIC-BENTHIC INTERACTIONS

Energy flows through an ecosystem by means of food web processes, starting with photosynthesis at the lowest trophic level and ending with large fish. An understanding of food web interactions is necessary before the effects of anthropogenic inputs and changes on the ecosystem can be predicted. For example, the pathways of organic contaminants through biotic systems may be directly related to the transfer of energy from one trophic level to the next; understanding how fisheries management actions produce an effect on water quality requires an understanding of food web interactions between phytoplankton and fish. GLERL's former Eutrophication and Nutrient Cycling project has evolved into a new project focusing on food web dynamics in the Great Lakes.

Previous results from a study on the effects of silicon limitation on phytoplankton species succession showed that diatoms have a phosphate uptake system that functions more efficiently than other algae at low substrate concentrations. However, under silicon-limiting conditions, the ability of diatoms to utilize phosphate was diminished, triggering a shift to blue-green algal dominance. During FY 1986 new computer simulations were used with the data to determine the reason for the loss of efficiency under silicon-limiting conditions. The results revealed that the cause is a loss of phosphate affinity by the diatoms' phosphate uptake system. This mechanistic information helps us to understand the role of the limiting nutrient in shaping phytoplankton community structure.

Silica and phosphorus fluxes were calculated from Lake Michigan sediment cores and revealed that dissolved silica fluxes are 3 orders of magnitude larger than dissolved phosphorus fluxes. Comparison with other sources of nutrients demonstrated that sediment fluxes are more important to the internal recycling of silica than to that of phosphorus.

In FY 1985, techniques to measure denitrification (conversion of nitrate to nitrogen gas) rates in lake sediments were perfected and a field program to examine this process began. In FY 1986 the results from a seasonal study of nitrogen transformations and fluxes in Lake Michigan sediments at two stations indicated that denitrification is a major sink for mineralized nitrogen in silty Lake Michigan

sediments and that flux of ammonium or nitrate from the sediments into the overlying waters is minimal.

Lipids (fats) are the compounds organisms primarily use to store energy. Materials from a series of sediment traps collected from Lakes Michigan and Huron were analyzed for lipid content to provide information on the magnitude and mechanisms of biochemical energy transfer from the pelagic to the benthic systems in these lakes. Preliminary analysis indicates that the largest contributors to the lipid fraction in sediment trap materials were hydrocarbons, pigments, and free fatty acids.

Benthic Ecology

A GLERL biologist who participated in the first exploration of Lake Superior with a research submersible completed his comparison of benthic samples to evaluate the sampling efficiency of Ponar grab samplers. Samples collected with the Johnson Sea Link II were compared with those collected using a Ponar grab sampler from the same locality. Abundances of all the major benthic groups were found to be underestimated from Ponar samples. During FY 1986 the field work using the submersible was extended into Lake Huron.

A new method using a computer digitizer and menu-driven software was developed to measure body length and gut fullness of the amphipod *P. hoyi*. This new method is more accurate and precise than earlier methods and provides a rapid and efficient way to transfer raw data to an on-line computer file.

WATER MOVEMENTS AND TEMPERATURE

Winter Bottom Circulation in Lake Michigan

Previous studies of the bottom boundary layer established the characteristics of a bottom Ekman layer in southern Lake Michigan, which produces veering of the near-bottom currents. Winter storms resuspend bottom sediments, causing a redistribution of materials deposited during the summer months, final deposition being determined by the overall winter circulation pattern and the Ekman dynamics of the bottom boundary layer. During the last week of April 1986, GLERL recovered several arrays of current meters moored near the bottom of Lake Michigan. The arrays had been deployed in November 1985 to measure the vertical profile of horizontal currents in the bottom boundary layer during the winter storm season.

Numerical Model of Lake Circulation

Accurate prediction of the movement of contaminants, nutrients, and suspended sediments in the Great Lakes depends on the accuracy of numerical lake circulation models in predicting currents. During FY 1986 an alternative to the traditional method of testing model accuracy was developed and applied to GLERL's numerical lake circulation model. The results revealed that the GLERL model shows significant skill in predicting particle trajectories over the course of a storm event. Quantitative bounds were established for the accuracy of trajectory predictions from the GLERL numerical lake circulation model.

OPTIMIZATION, UNCERTAINTY, AND RISK ANALYSIS APPLIED TO ENVIRONMENTAL SYSTEMS

Contaminant Management Models

Development of contaminant management plans that balance acceptable environmental risks against acceptable costs is a major goal of the Great Lakes community. Optimization, uncertainty, and risk analysis techniques are useful tools for achieving this goal, but have been used only sparingly to date. GLERL established a program in late FY 1984 to explore the application of these techniques to improving the management strategies for Great Lakes natural resources.

During FY 1986 GLERL completed a first-generation optimization model that takes uncertainty into consideration when determining the cost-effectiveness of contaminant treatment strategies. Management of phosphorus loading was chosen as a test case because of the importance and cost of dealing with this problem, the availability of a large, reliable data base, and the existence of tested phosphorus mass-balance models for the lakes. The results showed that there is a range of goal-achievement vs. cost, for consideration by resource managers. Strategies specified under the 1978 Water Quality Agreement between the United States and Canada are not likely to achieve more than 60% of the goal, whereas those identified through the optimization model are less costly and more effective.

Plans FY 1987

CYCLING OF TOXIC ORGANICS

- An extensive set of contaminant partitioning data will be analyzed for later use in modeling the long-term behavior of trace hydrophobic contaminants in aquatic systems.
- The rate of desorption of a suite of hydrophobic organic compounds will be measured in the laboratory to estimate the rates of sediment-water exchange of toxic organic contaminants.
- New experiments will be performed using natural interstitial waters from sediments from several locations in Lake Michigan to allow further definition of natural DOM's effect on the bioavailability of organic contaminants.
- The role of sediments as a source of organic contaminants and their relative importance to accumulation in Great Lakes benthos will be further defined through a continuation of the field and laboratory program initiated 2 years ago.
- Dose-response experiments will be conducted to determine the relative sensitivities of Great Lakes invertebrates to common organic pollutants.
- A model designed to simulate the accumulation of organic pollutants by *Hexagenia limbata* (mayfly larvae) will be developed and coupled to a population dynamics model, to predict the movement of organic toxicants through their trophic level.
- Measurements of PAH concentrations in water, sediments, and associated benthos will be used to verify a contaminant uptake and bioconcentration model.
- The use of stable isotopes (e.g., carbon-13) to study biogeochemical pathways in the Great Lakes system will be explored.

ECOLOGICAL SUCCESSION AND TRENDS

- A conceptual model of first-order factors that control phytoplankton abundance, based on data from a study in Lake Michigan in 1983 and 1984, will be completed. It will then be analyzed and extended to simulate phytoplankton and zooplankton succession over a 10-year period of alewife decline (1975–1985) in the Great Lakes.
- The quantitative importance of autotrophic picoplankton relative to total primary production in Lake Huron will be determined. Preliminary studies indicate that picoplankton can account for much of and even all primary production in this lake.

- Feeding interactions between the freshwater calanoid copepod *Diaptomus sicilis* and algae of various shapes, sizes, and tastes will be explored using high-speed microcinematography. Related experimental results on predator-prey interactions between *Diaptomus* and rotifers will be analyzed.

- Abundance, metabolic characteristics, and in situ feeding of the predacious cladoceran *Bythotrephes cederstroemi*, a recent invader of the Great Lakes from Europe, will be examined in Lake Huron and Lake Michigan to determine the species' effects on Great Lakes food webs.

- Cooperative field experiments (with scientists from the University of Delaware and the Institute for Ecosystem Studies, Milbrook, NY) will examine bacterial growth and loss dynamics in Lake Michigan. Competition between algae and bacteria for phosphorus will also be examined in simultaneous studies.

- The competitive interactions that shape Lake Michigan phytoplankton community structure will be examined by quantifying orthophosphate uptake rates by silica- and phosphorus-deficient Lake Michigan diatom assemblages using a simulation analysis routine that predicts variations in limiting-nutrient uptake from the Michaelis-Menton model.

- Ponar grab samples of the deposit-feeding amphipod *P. hoyi* collected in Lakes Michigan and Huron during the 1986 field season will be processed and analyzed. Amphipod production will be estimated by documenting changes in abundance of *P. hoyi* size classes throughout the field season. Production data will be compared with net carbon (detrital) input estimated from sediment trap data at the same sampling sites.

- Predator-exclusion experiments on *P. hoyi* will be continued in Lake Superior, using the Johnson Sea Link submersible, to evaluate potential effects of predation on long-term population changes of *P. hoyi* in the lakes.

- Pelagic and benthic long-term-trend studies will be continued in Lake Michigan. The benthos of Saginaw Bay will be sampled for comparison with previous benthic surveys of this region.

- Analyses of samples and data collected during the under-ice ecology pilot field experiment in Grand Traverse Bay in FY 1986 will be completed; changes in feeding, lipid content, and reproduction of zooplankton will be related to changes in the ice cover and phytoplankton concentration.

- A report will be prepared describing the ice physics associated with the under-ice ecology pilot field program conducted during FY 1986.

FOOD WEB DYNAMICS AND PELAGIC-BENTHIC INTERACTIONS

- The relative importance of carbon and phosphorus in limiting growth of autotrophic picoplankton and bacterioplankton in Lake Huron will be examined and the importance of the micro food web to carbon cycling in the lake will be quantified.

- Methodology will be developed to determine lipid composition in various groups of Great Lakes invertebrates. It will be used to provide information about how biochemical energy moves through various food web components in the Great Lakes.

- The seasonal lipid content and composition of *D. sicilis* will be examined to answer questions about food limitation, competition with the cladocera, and reproductive strategy of this pelagic invertebrate.

- Amino acid production and mineralization by different components of the pelagic food web will be examined by observing amino acid and ammonium concentration changes in light:dark bottle experiments subjecting lake water to various treatments including differential filtration and substrate additions. This study will provide seasonal information about the production and degradation of organic matter by various groups of organisms.

- Seasonal feeding habits of *P. hoyi* will be documented using gut-fullness data collected in the 1986 field season.

- A study on the physiological response of *P. hoyi* to food removal will be conducted to obtain information on why this important prey organism thrives in the upper Great Lakes where food supply is discontinuous.

- Nitrogen mineralization and denitrification will be examined in sediments from a eutrophic bay and compared with results from open-lake sediments to determine differences in mechanisms and rates of sediment mineralization in the two types of Great Lakes environments. The relative contributions of benthic invertebrates and microbes in organic nitrogen mineralization will be quantified.

WATER MOVEMENTS AND TEMPERATURE

- Measurements to quantify the thickness and structure of the bottom Ekman layer during winter resuspension events in Lake Michigan will continue.

- Observational data from current meters and satellite-tracked drifters will be compared with values generated by numerical models. Because the Great Lakes are simpler to survey than the oceans, the research has been very quantitative in the past and will continue to be so.

- The possibility of implementing GLERL's oil spill model (PATHFINDER) on microcomputers will be investigated.

- Existing models to predict lake thermal structure will be tested against observed temperatures in Lakes Erie and Michigan, and an improved version specific to the Great Lakes environment will be completed.

- A three-dimensional ocean circulation model developed at GFDL will be evaluated for possible merging with the GLERL modeling system to produce a better circulation model for the Great Lakes.

OPTIMIZATION, UNCERTAINTY, AND RISK ANALYSIS APPLIED TO ENVIRONMENTAL SYSTEMS

- A project will be initiated to evaluate and define (if possible) the probability distributions associated with Great Lakes lake levels, their implications to the environmental and economic interests of the region, and ways lake-level management strategies might be optimized, given the uncertainty about future lake levels.

MARINE HAZARDS AND LAKE HYDROLOGY

Marine Hazards and Lake Hydrology research focuses on (1) improving prediction of environmental phenomena associated with the National Weather Service (NWS) marine warning and forecast-

ing services and the U.S. Army Corps of Engineers (COE) regulation of Great Lakes water flow, and (2) providing better tools and methods for short- and long-term assessments of water resources of large lakes. GLERL research in these areas includes field and analytical investigations to develop simulation and prediction models of over-water wind and wind-waves, water surface oscillations, storm surges, and flooding; lake ice formation, growth, movement, and breakup; and hydrologic lake levels, water supplies and balance, and flows in the connecting channels. GLERL staff work closely with colleagues at the forecasting and warning service agencies to assure that GLERL products meet the needs of the operational forecasters. Products released to the user community continue to be improved by GLERL researchers, either by fine tuning, or by the addition of new tools and capabilities.

Accomplishments FY 1986

SURFACE WAVES AND WATER LEVEL FLUCTUATIONS

The primary driving forces for water movements in the Great Lakes are the wind acting on the surface, the exchange of heat across the water-atmosphere boundary, and the hydraulic flow through the system. Wind-generated surface waves can be a significant hazard to ships and recreational boaters, and storms can produce rapid short-term elevations of water level in the shallower bodies of water such as western Lake Erie, Green Bay, and Saginaw Bay. The ability to predict wind-generated waves and seiching produced by storms is critical to the safety of marine users and shoreline property interests on the Great Lakes.

Shallow Water Wave Forecasting

Some of the most heavily populated and most intensely used areas of the Great Lakes are also the shallowest (Lake St. Clair, Green Bay, Saginaw Bay, and western Lake Erie for example). Although wave forecast methods for deep water are well developed, shallow water wave forecasting is still in its infancy. During FY 1986, GLERL initiated research on the effects of shallow water on wave dissipation and attenuation that includes both field experiments and development of applicable models (see Upper Great Lakes Connecting Channels Study).

Wave Height Studies and Models

GLERL staff continued to support the use of the GLERL Interactive Wave Prediction Model by marine forecasters at the NWS Great Lakes Weather Service Forecast Offices (WSFOs). This model, housed on the GLERL computer, was accessed more than 200 times by NWS forecasters during FY 1986.

It is known that long-term wave heights can be modeled by log-normal or Weibull distributions, and that wind speed can be represented by a Rayleigh distribution. During FY 1986, GLERL postulated joint distributions between wind speeds and wave heights and between wave heights and wave periods. Since wind data are generally obtainable, the existence of validated joint distribution models can lead directly from wind statistics to wave statistics. The GLERL postulate was also tested in FY 1986, and the results are being evaluated.

GREAT LAKES ICE

The seasonal ice and snow cover in the Great Lakes basin has a major effect on both the economic and social well-being of the community. It affects navigation, shoreline erosion and damage, hydropower generation, water supplies, fisheries, recreation, and local climate. Understanding, simulating, and forecasting the ice and snow cover require improved information on the formation, growth, movement, and decay of the ice cover; the extent, thickness, and water equivalent of the snow cover; a better definition of the characteristics of the snow and ice cover; and the development of numerical models depicting the processes governing freeze-up, areal extent, thickness, transport, and breakup of the ice cover, and metamorphosis and ablation of the snow cover.

Operational Ice Forecasts

A menu-driven computer algorithm was developed during FY 1985 for NWS to forecast ice conditions on the St. Marys River. The algorithm forecasts date of ice formation, ice growth, and date of ice loss. During FY 1986, procedures to access and run the algorithm, data input requirements, and forecast limitations were demonstrated and documented. Access to and support of the algorithm on GLERL's computer were provided to both NWS and the Army COE for use in making (experimental) operational forecasts during the 1985–86 winter season on the Great Lakes. The algorithm will be evaluated and refined over the next several winter seasons by comparing forecasts from the algorithm with actual data.

Degree-Day Climatology of the Great Lakes Region

An 81-year (1897–1977) degree-day climatology for the Great Lakes region was updated with the addition of data for 6 years (1978–1983). The cumulative frequency distribution of the seasonal maximum freezing degree-days at 25 stations for the base period 1897–1983 was used to revise a winter severity index developed in an earlier study. Winter severity class limits were developed for each of the Great Lakes. The period of the update is remarkable in that it contains some of the most severe and one of the mildest winters of the whole 87-year base period.

Spectral Reflectance of Ice and Snow

During FY 1985, airborne spectral reflectance measurements (400–1100 nm) of old snow, open water, and several ice types were made on Saginaw Bay and were corrected for atmospheric attenuation and path radiance effects by using a combination of existing standardization techniques (light and dark secondary standards calibrated against a barium sulfate primary reference standard panel).

Other studies that have used a barium sulfate panel for a primary standard have assumed that it behaves like a perfect diffuse (Lambertian) reflector and therefore follows Lambert's cosine law (with illumination normal to the surface, the intensity or reflectance from a Lambertian surface varies as the cosine of the angle of view, but has a constant radiance of 1). During FY 1986 the barium sulfate reference panel used by GLERL as the primary standard for the field calibrations was tested for cosine response at different incident angles and wavelengths. Deviations from a perfect cosine response were documented for most angles and at all wavelengths measured, leading to the conclusion that the airborne data must also be corrected for errors due to the imperfect cosine response of the reference panel. The FY–1985 data were corrected for the observed cosine response errors of the primary calibration panel, resulting in a 2–4% decrease in reflectance for the ice types measured.

HYDROLOGIC PROPERTIES

The availability of adequate supplies of fresh water is potentially one of the country's most serious long-range problems. The Great Lakes, with a total combined surface area of 247,000 km^2, contain 23,000 km^3 of water, or approximately 95% of United States fresh surface water. This water is used for navigation, drinking, industrial processes, hydropower, irrigation, transportation, and wildlife and fish habitat. Major changes in water quantity are caused by annual and seasonal variations in the water supply, consumptive use, and interbasin diversions. The usual measure of water quantity is the lake level of the individual lakes. Over the past 120 years the levels have fluctuated about 2 m, and the normal seasonal fluctuation has been 35–50 cm between winter minimum and summer maximum. Superimposed upon the natural fluctuations are a number of anthropogenic changes which have or could have major effects on Great Lakes water quantity. During 1985, high lake levels set records on Lakes Superior, Michigan, Huron, St. Clair, and Erie. GLERL's hydrologic research program is directed toward improving our knowledge of the hydrologic and hydraulic processes, improving methods of forecasting and simulating water supplies and lake levels, and improving large-river dynamic flow models. The research assists in water resource planning and management and in the solution of prob-

lems related to water supply, water quality, shore erosion, flooding, hydropower, navigation, and recreation.

Rainfall-Runoff Modeling

Deterministic forecasts (outlooks) of accumulated net basin water supply are required in near-real time for use in regulating water levels of large lakes. The GLERL Large Basin Runoff Model was developed for this purpose several years ago. This general model has been modified and refined to improve and apply it to the Great Lakes. To calibrate the model each lake is divided into subbasins that drain into that particular lake, and then all available historical data for all subbasins about the lake are used to perform the initial calibrations. Initial calibrations are complete for Lakes Ontario and Superior. In FY 1986, the initial calibration, using a daily computation interval, was completed for each of the subbasins about Lakes Erie and Michigan. For Lake Erie, the distributed-parameter application to each of the 21 subbasins yielded a root-mean-square error of 0.62 mm over the basin and a correlation of 0.88. For Lake Michigan, the distributed-parameter application to each of the 27 subbasins yielded a root-mean-square error of 0.20 mm over the basin and a correlation of 0.92.

Water Supply Forecasting

In FY 1985, GLERL completed a semi-automatic software package to predict water supplies to Lake Superior in near-real time. During FY 1986, monthly outlooks of Lake Superior basin moisture, runoff, and water supplies were issued to a select group of users. In addition to these monthly outlooks, the Army COE, Detroit District, was supplied with lake level outlooks for Lake Superior. An error analysis revealed that about 20% of the error in the GLERL forecasts derives from NWS weather outlooks. About half the remaining error results from modeling lake evaporation.

Development of a generic Thiessen weighting package was completed. The generic package is easily applied to different areas and to different types of data. It was installed on the Detroit COE's Harris 500, the Chicago COE's IBM–PC, the NWS Northeast River Forecast Center's (NERFC) Nova Eclipse, and the NWS Office of Hydrology's (OH) Airborne Gamma Radiation Snow Survey IBM/PC–AT. The Army COE, Detroit District, and the NWS NERFC use it to make near-real-time areal estimates of snow water equivalents from aerial surveys of Lakes Superior and Champlain, respectively. The NWS OH Snow Survey Program uses the generic Thiessen weighting package for the Lake Superior and Lake Champlain basins and expects to use it for other areas where aerial snow surveys are conducted (Souris-Red-Rainy basin and St. Johns River basin).

Lake Superior Water Balance

Analysis of thermal corrections to Lake Superior's monthly change in storage, based on Expendable Bathythermograph transects made during 1976, revealed that the thermal component of change in lake storage is an important factor in the water balance of that lake. Thermal change in lake storage was largest during the period of thermal stratification (July, August, and September) when it accounted for more than 10% of the uncorrected change in storage. Thermal effects on net basin water supply (NBS) were found to be more than 100% of the uncorrected NBS in January and between 12% and 70% of uncorrected NBS in February, July, August, and September of 1976.

Lake Level Simulation

GLERL's Great Lakes Hydrologic Response Model, developed several years ago, models the hydrologic water balance through the Great Lakes system. It integrates the hydrologic components and routes the water through the system into the St. Lawrence River. The model provides the resulting lake levels for each of the Great Lakes and Lake St. Clair, and the flows in the connecting channels. During FY 1986 the Hydrologic Response Model was simplified, extensively documented, and recalibrated to reduce the error in modeled Lake Michigan–Huron levels. Analyses using this model provided several useful insights relative to the present high Great Lakes water levels. The analyses indicated that, although the lake levels are not likely to rise dramatically (e.g., on the order of several feet) over the next few months, neither are they likely to return to their 1900–1969 normal levels in the near future.

Seasonal Influences on River Flows

The St. Clair and Detroit Rivers are major connecting channels between Lake St. Clair and Lakes Michigan-Huron and Lake Erie, respectively. Ice buildup and jamming in the St. Clair River can have a significant effect on the seasonal cycle of water levels in the Great Lakes. Ice buildup reduces the channel capacity of the rivers, resulting in water storage in Lakes Michigan and Huron and reduced flows in the rivers, especially the St. Clair River. Reduced flow in the St. Clair River can have a significant effect on the level of Lake St. Clair. Wind set-up in Lake Erie can push water into the west end of the lake, which can result in a flow reduction and a short-term flow reversal in the Detroit River. The latter may provide a mechanism for the transport of contaminants from the Detroit River into Lake St. Clair.

The St. Clair River Winter Flow Experiment was extended through the 1985–1986 winter season and has provided five consecutive years of winter flow data for the St. Clair River. Data over two consecutive winter seasons have also been collected for the Detroit River (Detroit River Winter Flow Experiment). The results of this multiyear experiment have demonstrated the feasibility of using in situ current meters to monitor winter flows. However, it was shown that electromagnetic current meters are not appropriate for such measurements, owing to the significant loss of sensitivity caused by frazil ice during the winter and by weeds during the summer and fall. Acoustic Doppler current meters, on the other hand, work well in spite of these conditions. The data were also used to evaluate the St. Clair–Detroit River flow transfer method, which was found to be very useful when one of the rivers is free of ice problems.

During FY 1986, historical data were examined for evidence of possible flow reversals in the Detroit River during 1900–1985. Eight possible occurrences were identified and selected for further analysis, including one major episode that occurred in April 1984 (when GLERL had meters in the river) and coincided with a massive St. Clair River ice jam. At this time there was a reverse flow into the lake, with rates ranging up to a maximum of 2500 $m^3 s^{-1}$ for several hours. A second major episode may have occurred in February 1939. From this study it would appear that the main condition under which a flow reversal occurs is a severe ice jam on the St. Clair River coupled with a Lake Erie wind setup. Thus, although flow reversals are relatively rare events, they may provide a mechanism for the transport of contaminants into Lake St. Clair.

Plans FY 1987

SURFACE WAVES AND WATER LEVEL FLUCTUATIONS

- A field experiment will be conducted to measure wave spectra near the middle of the Western Basin of Lake Erie.
- A field program for shallow-water wave measurements will be conducted in Lake Erie to extend the results of the Lake St. Clair WAVEDISS '85 experiment (see Upper Great Lakes Connecting Channels section, below).
- The feasibility of transporting the VAX-based Interactive Wave Forecast Model to a standard IBM–PC microcomputer will be explored in response to a request from the NWS WSFOs in the Great Lakes region.

GREAT LAKES ICE

- A program will be initiated to define the spectral transmittance of solar radiation in the visible and near-infrared ranges through various types of ice and snow covers.

- The measurements demonstrating the non-Lambertian character of sprayed barium sulfate reference panels, and the resulting corrections, will be documented in the published literature.
- Lake Erie satellite data from 1982 will be analyzed to document changes in lake-wide ice and snow albedo occurring on a monthly time scale over one season.
- A field program to determine changes in albedo with changing solar altitude and sky conditions will be conducted in cooperation with scientists at NASA's Goddard Space Flight Center.
- Interpretation and classification of Great Lakes ice cover from the NOAA–9 (AVHRR) digital satellite imagery of 21 March 1985 will be completed.
- A study of ice rafting/ridging scouring processes will be initiated.
- A report on past ice and snow research in the Great Lakes will be completed.
- A study to define the engineering properties of nearshore ice thicknesses will be completed..
- Verification of the St. Marys River operational ice forecast techniques will be continued in conjunction with the Army COE and NWS.
- A catalog of pertinent meteorological parameters and associated ice cycle types will be developed for use by NWS in relation to ice forecasting.
- A program will be initiated to develop methods to analyze the effects of climatic change on Great Lakes ice cycles.

HYDROLOGIC PROPERTIES RESEARCH

- Lake evaporation forecast techniques based on lake surface temperatures and meteorologic outlooks will be developed for each of the Great Lakes, and integrated into our water supply outlook package.
- System-wide lake-level forecast techniques that incorporate water supply outlooks, hydraulic routing, and regulation plans for the Great Lakes, will be completed. The usefulness of the techniques will also be assessed.
- System-wide models of Great Lakes hydrology will be used to assess the effects of climatic change, increased consumptive uses, and interbasin diversions on water levels, and the practicability of regulations and diversions for reducing lake level extremes.
- Perspectives on the causes and consequences of the record high Great Lakes water levels, and the potential for continued high levels, will be presented at public forums and in technical and general articles.
- The Great Lakes hydrometeorologic monthly data base of basin runoff, air temperatures, precipitation, evaporation, connecting channel flows, diversions, net basin supplies, and changes in lake storage will be extended with daily data, when available, through 1986.
- System-wide models of Great Lakes hydrology will be integrated with water quality, ecosystem, and economics models, making possible assessments of the effects of water quantity management on the Great Lakes ecosystem and regional economics.

- The implications of water quantity management alternatives for lake level regulations will be examined.
- Field measurements for St. Clair River Winter Flow Experiment will be completed. Existing unsteady flow models will be recalibrated to include ice effects, and winter flows for 1959–85 will be recomputed.
- An acoustic Doppler current profiler will be deployed in the Detroit River to supplement the measurements for the Detroit River Winter Flow Experiment.

UPPER GREAT LAKES CONNECTING CHANNELS STUDY

The Upper Great Lakes Connecting Channels Study (UGLCCS) is an international (U.S.-Canada) and interagency multiyear study of water quality and ecosystem dynamics in the upper Great Lakes connecting channels. Study areas include the St. Marys River, the St. Clair River, Lake St. Clair, and the Detroit River; all are designated by the International Joint Commission as "Areas of Concern" in which environmental quality is degraded, and beneficial uses of the water and biota are adversely affected. The goals of the study are (1) to determine the existing environmental condition of the study areas, (2) to identify and quantify the effects of contaminant loading on human and ecosystem uses of the study areas, (3) to determine the adequacy of existing or proposed programs for ensuring or restoring beneficial uses, and (4) to recommend appropriate programs for protecting the study areas.

Accomplishments FY 1986

ENVIRONMENTAL MODELS OF LAKE ST. CLAIR

Ecosystem Model

A conceptual ecosystem model was developed for Lake St. Clair for the purpose of understanding the dynamics of shallow (near-shore) systems and how the dynamics will affect the fate and transport of contaminants. Approximately one-half of the data necessary for parameterizing this model have been obtained. The results will be used by the adapted TOXIWASP model (see below).

Contaminant Fate-and-Effects Models

The U.S. EPA model TOXIWASP was selected as the basis for a model to predict the fate, transport, and effects of contaminants in Lake St. Clair. During FY 1986, TOXIWASP was adapted for use on both the GLERL VAX and Department of Commerce Consolidated Scientific Computing Service CYBER computers, debugged, and run through a complete sensitivity analysis of all its rate-governing coefficients. Ecological data and hydrodynamic simulations are being used to improve the prediction capabilities of the TOXIWASP model so it can be used to forecast the effects of contaminants on important aquatic organisms during their critical life stages.

A prototype toxic contaminant fate-and-effects model was developed for plankton systems. The state-of-the-art framework developed in this model is being used to predict the effects of contaminants on plankton populations. Preliminary results from this model indicate that it may be unwise to model contaminant effects without also modeling contaminant fate.

GLERL's previously developed Coupled Lakes Contaminant Fate Model was applied to estimate the time dependence of fallout radionuclide loadings to Lake St. Clair and the connecting channels. The calculation showed that the dominant source of Cs-137 in Lake St. Clair is inflow from Lake

Huron, and if all the radionuclides were retained in the system, on the average, about 100 dpm cm^{-2} should be found in sediments of this lake today.

Phosphorus Model

A phosphorus mass balance model for Lake St. Clair was completed. It was used to identify the relative importance of phosphorus loading sources (Huron > Diffuse Runoff >> Atmospheric & Point). Model results revealed that the variability in average phosphorus concentrations is equally due to variability in external and in internal (by resuspension) loads.

St. Clair River Flow Models

An unsteady-flow mathematical model is being developed for the entire St. Clair River, including flow distribution around islands in the single upper river channel and separation of flow through the main channels in the river delta. A model for the single channel area has been extended and calibrated from St. Clair to Algonac, providing two model versions that indicate single channel flows and separation of flows around the Stag and Fawn islands. Work on the entire river model, including the delta, continues.

FIELD AND LABORATORY EXPERIMENTS

Nutrients and Contaminants

Microcosm experiments for determining phosphorus release from Lake St. Clair sediments were completed. Inorganic phosphorus excretion by clams appears to be a very important process in Lake St. Clair, amounting to about 25% of all other inputs of bioavailable phosphorus to the lake.

Extensive coring was undertaken in Lake St. Clair during May and September 1985 in collaboration with the Canada Centre for Inland Waters. The operation resulted in acquisition of diver-collected sediment cores from an evenly spaced grid covering most of the fine-grained sediments in the lake. Two cores were collected from each of 36 sites and sectioned in the field. The materials were divided between the participating institutions for laboratory analysis. Initial results show a regular pattern of storage, on the order of 10–20 dpm cm^{-2}, with pronounced accumulation of Cs-137 in areas of fine-grained sediments (generally the deepest areas of the lake). Thus 10–20% of the total loading of the radionuclide to the system appears to remain in bottom deposits. Completion of all sample and data analyses will allow us to refine and finalize these results.

Currents and Circulation of Lake St. Clair

In FY 1985, three 1-week-long synoptic current surveys were conducted in Lake St. Clair to observe and measure flow throughout the basin under calm and storm wind conditions. Analysis of these data, involving reduction of the raw data to measured currents and comparison of the measured currents with circulation model predictions, was essentially completed in FY 1986.

Waves Study

During late FY 1985 and early FY 1986, GLERL and NWRI (Canada) performed an extensive joint field measurement program in Lake St. Clair to measure wave dissipation and the effect of waves on resuspension in shallow water (WAVEDISS '85: Wave Attenuation, Variability, and Energy Dissipation In Shallow Seas). Analysis of the data during FY 1986 included (1) selection of appropriate episodes for study of wave dissipation effects, (2) spectral analysis of wave measurements, (3) calculation of wave dissipation based on differences in the wave spectra, and (4) comparison of experimental values with values calculated from existing theories of wave dissipation in shallow water.

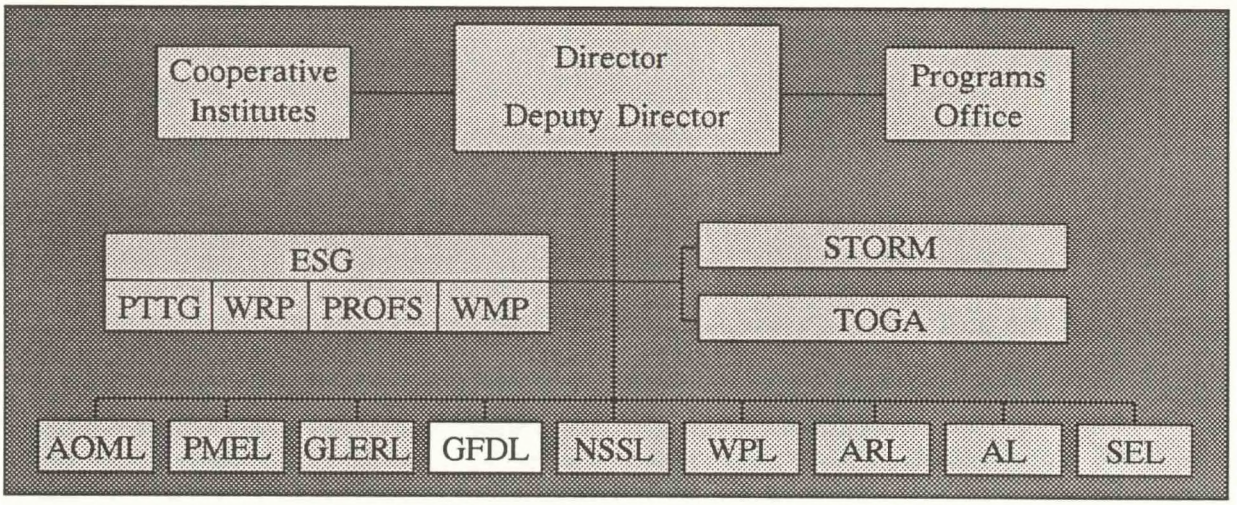
Plans FY 1987

ENVIRONMENTAL MODELS OF LAKE ST. CLAIR

- A generic contaminant fate and transport model will be developed for Lake St. Clair and will be calibrated using data from GLERL research on Lake St. Clair cesium loads and sediment profiles.
- An ecosystem model will be developed to understand ecological processes in Lake St. Clair and how they affect contaminant fate and behavior.
- Development and documentation (model program/report) for the Unsteady-Flow Model of the entire St. Clair River will be completed.

FIELD AND LABORATORY EXPERIMENTS

- Experiments will be conducted to determine the filtering rates and particle-size selection of mussels in Lake St. Clair on a seasonal basis.
- Time-series current and light transmission data from the bottom boundary layer in Lake St. Clair will be analyzed. Results will be used in sediment transport models.
- Sediment radionuclide retention characteristics in systems with short hydraulic residence times, such as Lakes St. Clair and George, will be examined. Non-steady-state transport and diagenesis models will be used to interpret data collected in the UGLCCS program as well as other similar systems.
- Analyses of data on wave dissipation and wave effects on resuspension in Lake St. Clair, obtained during the WAVEDISS '85 field experiment, will continue.



GEOPHYSICAL FLUID DYNAMICS LABORATORY

Princeton, New Jersey

J.D. Mahlman, Director

The Geophysical Fluid Dynamics Laboratory (GFDL) is engaged in comprehensive long-lead-time research fundamental to NOAA's mission. The goal is to expand the scientific understanding of the physical processes that govern the behavior of the atmosphere and the oceans as complex fluid systems. These fluids can then be modeled mathematically and their phenomenology studied by computer simulation methods. In particular, GFDL research concerns the following:

- Complete analysis of selected 1984 cores to determine the along-channel and cross-channel patterns of organic pollutant accumulations in Puget Sound.
- Predictability of weather, large and small scale.
- Structure, variability, predictability, stability, and sensitivity of climate, global and regional.
- Structure, variability, and dynamics of the ocean over its many space and time scales.
- Interaction of the atmosphere and oceans; how the atmosphere and oceans influence and are influenced by various trace constituents.
- Earth's atmospheric general circulation within the context of the family of planetary atmospheric types.

The scientific work of the Laboratory encompasses a variety of disciplines: meteorology, oceanography, hydrology, classical physics, fluid dynamics, chemistry, applied mathematics, and numerical analysis. Research is facilitated by the Geophysical Fluid Dynamics Program, which is conducted collaboratively with Princeton University. Regular Princeton faculty, GFD Program scientists, and graduate students participate in theoretical studies, both analytical and numerical, and in observational experiments, in the laboratory and in the field. The program is supported, in part, by NOAA funds. GFD Program scientists may also be involved in GFDL research through institutional or international agreements, or through temporary Civil Service appointments.

WEATHER SERVICE

During the past two decades synoptic-scale weather forecasts have improved considerably because of the development of numerical models that include more of the physical processes of the atmosphere, that have high spatial resolution, and that parameterize turbulent processes more accurately. Successful forecasts for periods up to a few days are now possible, and the limits of atmospheric predictability have been extended to several weeks. However, quantitative precipitation forecasts remain elusive. For smaller spatial scales, there has been considerable progress in determining the mechanisms that generate severe storms, in explaining how mesoscale phenomena interact with the large-scale flow, and in simulating the genesis, growth, and decay of hurricanes.

This success in the extension of atmospheric predictability encourages us to pose more challenging questions. Can the weather be predicted on time scales of months? Are mesoscale weather systems and regional-scale precipitation patterns predictable, and if so, is the accuracy dependent on the prediction of the ambient synoptic flow? Research to develop mathematical models for improved weather prediction will also contribute to the understanding of such fundamental meteorological phenomena as fronts, hurricanes, severe storms, and tropospheric blocking.

Accomplishments FY 1986

A new parameterization of gravity wave drag was developed and tested in a long-range forecast model. The new parameterization was found to improve forecast skill substantially; this result is consistent with results on the importance of gravity wave drag found at other institutions, including the U.K. Meteorological Office.

Results of monthly forecasts for eight January cases indicate that the model's systematic biases (climate drifts) account for a large portion of the forecast errors. For example, in the tropics, climate drift is responsible for 83% of the forecast errors in temperature at 300 mb; in the Northern Hemisphere, the climate drift is responsible for 64% of the forecast errors in the 500-mb geopotential height for the 10–30 day range.

A fundamental new fluid dynamical instability was discovered. This mechanism breaks down noncircular two-dimensional vortices into small-scale three-dimensional structures. This instability is believed to have a major role in the onset of turbulence in small-scale flow.

A simulation of the tropical ocean was completed; the model has $1° \times 1°$ spatial resolution globally, which is increased to $1/3°$ meridional resolution in the equatorial zone, and has 12 vertical levels. The model incorporates a turbulence closure scheme and a nonlinear viscosity for lateral diffusion. A test of this model for the 1982–83 El Niño case shows satisfactory performance; however, the effect of coarse vertical resolution is apparent. This model will be coupled to an atmospheric weather prediction model in the near future. Further study of the effect of mountains on the behavior of tropical cyclones showed that storm structure sometimes becomes considerably altered or disorganized while the storm is crossing the island terrain or afterward, making the storm position almost undefinable.

The simulation results of the genesis of real tropical storms indicate that some of the tropical disturbances at prestorm stage are significantly controlled by synoptic-scale conditions and, hence, they are predictable to a certain degree.

A theoretical study of the classical Eady baroclinic model elucidated the influence of nongeostrophic effects on meso-baroclinic waves. The analysis also showed the existence of a secondary, weak instability due to inertial critical layers.

A successful simulation of cyclogenesis on the lee of the Tibetan Plateau was recently completed. Vortices frequently produce heavy rainfall in the region and were believed to be caused by orographic effects. The numerical simulations indicate that orography alone triggers only weak vortices; however, in the presence of a moist stagnation region on the eastern flank of the plateau, these vortices intensify.

The effect of mesoscale forcing and diabatic heating on the formation of convective systems was investigated in realistic simulations of a squall line that developed over Texas and Oklahoma on 10–11 April 1979. The results of these experiments show that low-level convergence alone is sufficient in this case to initiate and organize the observed cloud systems. However, latent heating must be present to produce the observed deep convection and to maintain the low-level convergence.

The moist convection model was updated to include subgrid-scale condensation below cloud base and the concomitant latent heat release. For both shallow and deep convection, this scheme tends to produce a more uniform vertical velocity and to maintain the cloud over a longer lifetime by supplying low-level heating. For shallow convection, rain reaching the ground is increased significantly.

Plans FY 1987

Numerical models will be under continual development to improve forecasting of the large scale, the mesoscale, hurricanes, and squall lines, with emphasis on improved parameterizations of orography, cloud-radiation interaction, and various subgrid-scale effects.

Diagnostic analysis will be employed to improve understanding of essential weather processes relevant to prediction of atmospheric and oceanic phenomena with short, medium, and long time scales.

Collaboration will continue with the National Meteorological Center, in the development of both the Medium Range Forecast Model and a new operational model for hurricane prediction.

CLIMATE

The purpose of climate-related research at GFDL is twofold: to describe, explain, and simulate climate variability on time scales from seasons to millennia; and to evaluate the climatic effect of human activities such as the release of CO_2 and other gases in the atmosphere. The phenomena that are studied include large-scale wave disturbances and their role in the general circulation of the atmosphere; the seasonal cycle, which must be defined before departures from the seasonal cycle (interannual variability) can be understood; interannual variability associated with phenomena such as the El Niño-Southern Oscillation (ENSO); very-long-term variability associated with the ice ages; and the meteorologies of various planets, the study of which enhances our perspective on terrestrial meteorology and climate. To achieve these goals, both observational and theoretical studies are necessary. Available observations are analyzed to determine the physical processes by which the circulations of the oceans and atmospheres are maintained. Mathematical models are constructed to study and simulate the ocean, the atmosphere, the coupled ocean, atmosphere and cryosphere system, and various planetary atmospheres.

Accomplishments FY 1986

To study the role of land surface processes in climate variability, a 50-year integration of a general circulation model (GCM) with prescribed sea-surface temperatures and cloudiness was conducted. Analysis shows that while the spectrum of precipitation over land is white at all latitudes, the spectrum of soil moisture (driven by the precipitation forcing) is red, and becomes increasingly red at higher latitudes. This may be the result of reduced potential evaporation and insolation at higher latitudes.

The role of geography in the transient response of an atmosphere-ocean model to a doubling of atmospheric CO_2 was investigated. An idealized model with two hemispheres was used in which the fractional coverage of continent and ocean at each latitude is approximately equal to the actual coverage. At the latitudes of the Drake Passage, the domain is completely covered by ocean. The results indicate a much slower rate of surface warming in high latitudes of the Southern Hemisphere.

A series of experiments was conducted in which an atmosphere/mixed-layer ocean model was used to study the contributions of continental ice, atmospheric CO_2, and changes in land albedo to the climate of the last glacial maximum (LGM). These experiments indicate that the most important contributor to the LGM climate cooling in the Northern Hemisphere is the presence of expanded continental ice. In contrast, the cooling in the Southern Hemisphere is associated primarily with the reduced atmospheric CO_2 content of glacial times.

An analysis was made to determine the mechanisms responsible for the enhancement of the CO_2-induced warming of a model climate by cloud feedback processes. In response to a doubling of CO_2, both relative humidity and cloud amount are increased near the tropopause and are reduced in the middle troposphere. Thus, the effective cloud top height increases, thereby reducing the outgoing terrestrial radiation. On the other hand, the reduction of tropospheric cloud cover with a high albedo increases the net insolation received by the system. Both processes act to enhance the CO_2-induced warming of a model climate.

The extratropical atmospheric response to El Niño surface temperature conditions in the Pacific, as produced by a GCM, was diagnosed with idealized steady-state barotropic and baroclinic models. These calculations demonstrate that the wavetrain over the North Pacific and North America cannot be thought of as directly forced by tropical latent heating. The wavetrain is more directly forced by anomalous middle-latitude transient eddy momentum fluxes which must, in turn, be related to the anomalous tropical forcing.

Analysis of a spectral GCM integration and observation data from the First GARP Global Experiment (FGGE) shows that tropical intraseasonal oscillations take the form of an eastward-moving Kelvin mode near the Equator and an eastward-moving Rossby mode away from the Equator.

Analysis of a GCM with a flat, saturated, zero-heat capacity surface revealed the presence of eastward-propagating waves at the Equator with periods of 20–30 days, which closely resemble observed atmospheric oscillations with somewhat longer periods (about 40 days). The presence of these waves in such an idealized model allows one to analyze the underlying dynamics in detail and rules out some current theories for their generation. Surprisingly, a well-defined eastward-propagating tropical wave of even lower frequency (>100-day period) is also produced by this idealized GCM.

Results of experiments using a GCM with a zonally uniform surface indicate that cyclone-scale waves enhance transient ultralong waves in the growing stage by wave-wave energy transfer, but reduce these waves in the mature stage by reducing the mean baroclinicity through wave/mean-flow interactions.

A modeling study of the errors expected from use of the TIROS-N Operational Vertical Sounder (TOVS) satellite system revealed some pronounced effects. The satellite's analysis of the tropics is highly restricted owing to poor sampling and an inapplicability of geostrophic-type approximations. The regression technique currently used was found to be severely limited by its dependence on the quality of the available "ground truth" data used in the algorithm.

A set of model solutions was obtained for atmospheric circulations over a wide range of rotation rates and obliquity, moisture, and surface friction values. The results show that just five basic atmospheric circulation types emerge.

The frequency and geographical dependence of the mode of propagation and physical structure of observed and simulated transient fluctuations were analyzed using cross-spectral techniques. It was demonstrated that the current version of the GCM is capable of reproducing the full range of observed atmospheric phenomena with time scales from several days to a season.

The distinctions between the principal mode of atmospheric variability associated with internal dynamics and the anomalous circulation pattern accompanying ENSO episodes were highlighted by analyzing extended GCM simulations with and without sea-surface-temperature variations at the lower boundary. It was demonstrated that both internal atmospheric processes and external forcing are capable of imparting a considerable level of variability to the atmospheric circulation.

Plans FY 1987

A coupled ocean-atmosphere model with realistic geography will be used to investigate the transient response of climate to an increase of atmospheric carbon dioxide.

An attempt will be made to simulate the climate of the last glacial maximum by use of a coupled ocean-atmosphere model.

Detailed analysis will be continued on the spatial and temporal variability of soil wetness in the 50-year integration of a general circulation model of the atmosphere.

The stationary eddies produced by a variety of GCMs, both realistic (present, ice-age, and increased CO_2 climates) and idealized, will be analyzed and compared with the predictions of a linear stationary wave model.

A very efficient two-layer atmospheric model coupled to an oceanic mixed-layer model will be used for a preliminary study of the climatic response to orbital parameter variations.

Many diagnostic and theoretical analyses will be undertaken on transient and standing flows and on their interaction. Diagnostic analysis will continue with emphasis on global dynamical climatology, as well as an increased emphasis on regional problems such as those of the Southern Hemisphere, polar regions, southeast Asia, and the central Pacific.

ATMOSPHERIC QUALITY

The main goal of atmospheric quality research at GFDL is to understand the formation, transport, and chemistry of atmospheric trace constituents on regional and global scales. Such understanding requires judicious combinations of theoretical models and specialized observations. The understanding gained will be applied toward evaluating the sensitivity of the atmospheric chemical system to human activities.

Accomplishments FY 1986

A new hypothesis was advanced that the recent ozone "hole" over the Antarctic is the result of a natural but unusual dynamical process. The hypothesis asserts that the magnitude of winter dynamical forcing from the high-latitude Southern Hemisphere decreased significantly after about 1980. This reduced forcing, which has been identified in observational data, is shown to produce most of the major features seen in the ozone data.

A new shortwave radiation scheme was developed for the SKYHI model to simulate the radiative influence of aerosols. This new scheme allows investigation of a new class of climate-aerosol interaction problems.

The vertical mixing of passive tracers initially confined to the boundary layer was examined. Calculations with a moist convection model were carried out for a fully insoluble tracer, an infinitely soluble tracer, and a partially soluble tracer. Calculations for the partially soluble tracer were performed for SO_3. Preliminary results indicate that significant amounts of SO_3 are advected to upper cloud levels, a situation analogous to the vertical mixing of the fully insoluble tracer.

Plans FY 1987

Work will continue on the regional/global transport, chemistry, and removal of chemically and climatically important trace gases. A self-determined ozone chemistry will be inserted into the SKYHI GCM.

Moist chemical removal parameterization processes will be developed for use in convective and large-scale models.

MARINE QUALITY

Research at GFDL related to the quality of the marine environment has as its objectives the simulation of oceanic conditions in coastal zones and in estuaries, the modeling of the dispersion of geochemical tracers (tritium, radon, etc.) in the world oceans, and the modeling of the oceanic carbon cycle and trace metal geochemistry. For regional coastal studies, two- and three-dimensional models of estuaries such as the Hudson-Raritan and Delaware estuaries are being developed. The response of coastal zones to transient atmospheric storms, and the nature of upwelling processes (which are of great importance to fisheries), are being studied by means of a variety of models. Basin and global ocean circulation models are being developed for the study of the carbon cycle and trace metal cycling.

Accomplishments FY 1986

The ongoing analysis of data obtained during the Transient Tracers in the Ocean (TTO) North and Tropical Atlantic studies has led to a better understanding and clearer picture of the structure of the Deep Western Boundary Undercurrent and the benthic mixed layer.

Two cruises were completed during FY 1986. The first collected water samples for interlaboratory comparisons of radium measurement techniques. The second used tracers to study cross-Gulf Stream exchange in the North Atlantic.

A simulation of the entry of bomb-produced carbon-14 was completed. This study verifies that the World Ocean model contains the main downward pathways indicated by transient tracer data. The model allows a forecast of the bomb-produced carbon-14 distribution during the period of the World Ocean Circulation Experiment (WOCE), and demonstrates the usefulness of the model for predicting the response of the ocean to climatic transients on decadal time scales.

Plans FY 1987

An effort will be initiated to incorporate biological effects in a coupled carbon cycle/ocean GCM. A wide range of analyses of ocean tracer data relative to ocean dynamical structure will continue.

OCEAN SERVICES

Various models that can be used for the predicting oceanic conditions are being developed at GFDL. The simpler models are capable of predicting relatively few parameters. For example, one-dimensional models of the turbulent surface layer of the ocean predict the sea-surface temperature and heat content of the upper ocean. More complex three-dimensional models are being developed to study phenomena such as the time-dependent development of Gulf Stream meanders and rings, the generation of the Somali Current after onset of the southwest monsoons, the response of coastal zones to atmospheric storms, and the development of sea-surface temperature anomalies such as those observed in the tropical Pacific Ocean during ENSO phenomena.

Accomplishments FY 1986

A realistic simulation of the seasonal cycle in the tropical Atlantic Ocean permitted a study of the mass budget and indicated that upwelling near the Equator, and intense downwelling in adjacent latitudes, are of central importance in closing the horizontal circulation. Unusual conditions in the tropical Atlantic Ocean in 1984 resemble El Niño episodes in the Pacific in many respects, but a crucial difference is that the Atlantic has no counterpart to the eastward movement of the atmospheric convergence zone over the western Pacific.

The annual cycles of two monthly climatological sea-surface temperature fields were compared, using two different data sets: the relatively data-rich COADS (Comprehensive Ocean-Atmosphere Data Set) merchant ship data file (70 million ship reports), and the relatively data-sparse NODC (National Oceanographic Data Center) file (1.5 million sea-surface temperature measurements). The comparison showed that the NODC-based analyses capture the first two harmonics of the annual cycle quite well. This finding gives greater confidence in the representativeness of the analyzed subsurface thermal fields (and thus heat storage) that are based only on the sparse NODC files.

Computations of meridional Ekman heat transport in the world ocean were completed. The Indian Ocean exhibits an annual mean southward heat flux across nearly all latitudes from 28°N to 30°S. This southward flux is in agreement with heat flux estimates based solely on surface heat balance.

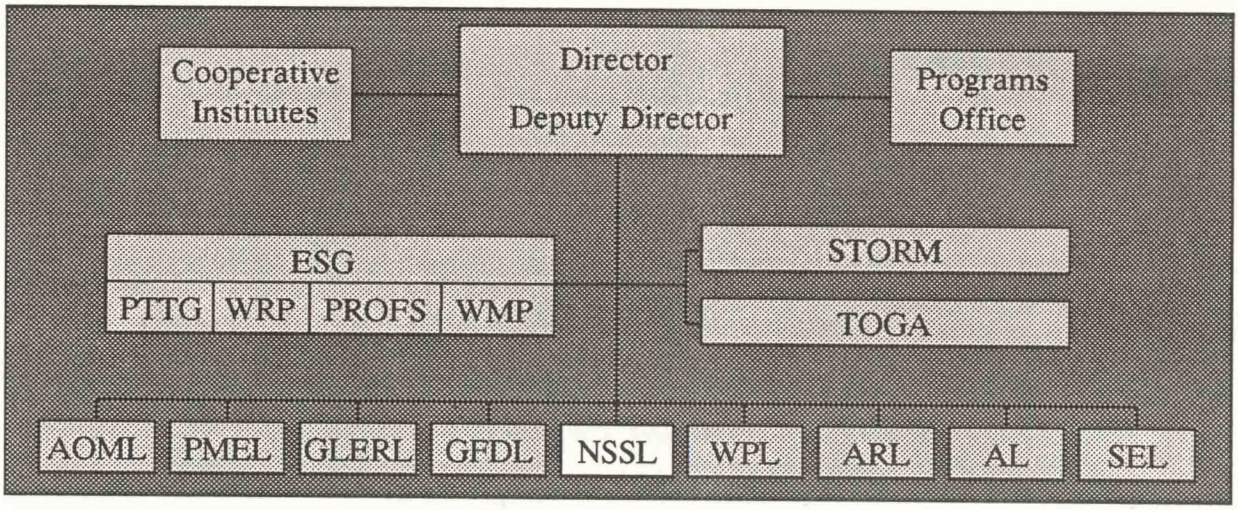
Plans FY 1987

Work will continue on the development of coupled ocean-atmosphere general circulation models. The capability of such models to simulate the interannual variability of the ocean-atmosphere system will be assessed.

Detailed analysis of the behavior of ocean models will be under way with special emphasis on the new higher resolution models.

Work will continue on ocean model developments with emphasis on ice dynamics, turbulent closure, and isopycnal coordinates.

Detailed comparisons of estuary model behavior against observations will be carried out.



NATIONAL SEVERE STORMS LABORATORY
Norman, Oklahoma
Robert Maddox, Director

The National Severe Storms Laboratory (NSSL) develops improved means for weather observing and forecasting through studies of storm processes, numerical and conceptual modeling of storm phenomena, and applications of new technologies in remote sensing. New technological developments, new scientific discoveries, and new requirements are reflected in changing approaches to achieving the goals of accurate precipitation forecasts and storm warnings well in advance of events. Recent studies have drawn heavily on observations by Doppler radar and lightning-mapping systems, and we have developed more effective methods for using Doppler radar and lightning data for forecasts and warnings of severe storms. During the coming year increasing emphasis will be given to the expansion of research to include larger scales of meteorological phenomena, and to the incorporation of modern research workstations and digital satellite data into case study analyses.

The work at NSSL, probably the most substantial precursor of the major national initiative NEXRAD (Next-generation weather radar), continues to support that program in critical ways. Other work at NSSL is providing a base in understanding to support deployment and use of national networks for lightning sensing. During two decades NSSL has examined individual storm cases to garner knowledge of physical processes in convective storms. These case studies continue, and we are now seeing significant maturation of both our knowledge and our observing tools. Means are within our grasp to extract substantial new meteorological information from radar data through utilization of diversely polarized transmissions and advanced capabilities in data processing. Our research efforts are starting to address the important problem represented by forecasting precipitation in the 0–24 hour range. There is a plan of action to begin bringing edge-of-the-art capabilities for computing, data synthesis, and analysis to the Laboratory during the coming year.

The Laboratory has a 50-station capability for observing and digital recording of surface meteorological parameters, and maintains instrumentation on the tallest tower in the United States that is equipped for recording boundary layer parameters. Two 10-cm Doppler radars on a 41-km baseline provide unique capabilities for recording atmospheric circulations both in precipitating weather systems and in the optically clear boundary layer. A comprehensive range of instrumentation for measuring parameters of both in-cloud and cloud-to-ground lightning has been brought to a high level of refine-

ment so that distributions of wind, water substance, and lightning can be recorded contemporaneously, and their interaction examined.

Through numerous relationships with other government agencies and universities, NSSL constitutes a resource for severe-storm data examined by researchers around the country and overseas. NSSL directly participates in many research projects outside Oklahoma. During FY 1986, NSSL staff participated in experiments involving lightning strikes to aircraft near Wallops Island, Virginia, assisted in interpreting Doppler radar returns from orographic thunderstorms during prior experiments in New Mexico, and had a major role in multi-agency field research programs conducted at Huntsville, Alabama, during the summer. A major effort in the Laboratory is directed toward establishing an effective national weather radar network for the late 1980s and beyond, in support of the NEXRAD Joint System Program Office, Silver Spring, Maryland. The Laboratory plans to work extensively with the National Weather Service (NWS) and the NEXRAD program during an expanded Doppler lightning experiment (DOPLIGHT–87), which will facilitate the operational transition to a modern radar system.

The Meteorological Research Group seeks to improve forecast and warning capabilities by developing conceptual, numerical, and laboratory models of major severe weather phenomena and of the prestorm atmosphere. Analysis and interpretation of storm flow fields expand our understanding of external and internal forcing, thermodynamics, cloud physics, electrification, and cloud dynamics, which contribute to intense thunderstorms and their attendant phenomena.

The objectives of the Doppler Radar and Storm Electricity Research Group include (1) determining relationships between lightning, thermodynamic, and precipitation processes in thunderstorms, to develop improved indicators of thunderstorm severity and hazards; (2) developing and refining remote-sensing techniques for locating, tracking, and predicting thunderstorms and their attendant hazards; (3) defining lightning and kinematic characteristics of storms for inputs into engineering criteria for hazards to aircraft and ground facilities, and into models used in environmental studies; (4) providing ground truth and supportive data for development of new and refined observational techniques. These objectives are addressed through both theoretical and observational studies. The Doppler Radar Group interprets prestorm and storm phenomena, using data from Doppler radar and other sensors. The Storm Electricity Group analyzes simultaneously Doppler radar and storm electricity data.

The Computer and Engineering Support and Development Group develops techniques and equipment, maintains the NSSL observational facilities, and supports the observational programs associated with meteorological research. The group also provides engineering consulting to the NEXRAD/Joint System Program Office and engineering support to the Interim Operational Test Facility.

METEOROLOGICAL RESEARCH

Accomplishments FY 1986

THUNDERSTORM EVOLUTION AND MORPHOLOGY

Flow patterns in and about the middle levels of thunderstorms are often compared with the patterns around obstacles embedded in a mean flow. A kinematic analysis of several supercell storms indicates that supercell updrafts lack expected obstacle properties. Critical Reynolds numbers necessary for producing counter-rotating vortex pairs are not reached by the mean flow. Hodographs derived from updraft wind data and from environmental rawinsonde data show remarkable similarities. The momentum of the low-level environmental wind is not preserved in the updraft. Anticyclonic eddies, common features of supercell storms, are a part of a vortex pair that forms as horizontal vortex tubes are tilted by vertical motions. Such eddies are not shed as an obstacle effect but rather form as the updraft dissipates and the updraft remnants move to the rear of the storm where anticyclonic vorticity prevails.

Dual-Doppler radar data for nearly 2 1/2 h, collected on 19 June 1980, document the transition of a multicell storm into a nearly-steady-state storm with supercell characteristics. Individual convective cells within the multicell storm increased in size and intensity while maintaining a nearly constant separation. A large region of weak background updraft, with embedded perturbations (maxima) representing individual cells, formed and propagated to the right of the mean wind. The differential motion of the persistent background updraft resulted in greater storm-relative streamwise vorticity, i.e., the component of vorticity in the direction of the storm-relative inflow wind, and consequently significant updraft rotation. Results suggest a continuum of storm types, rather than discrete categories.

Although the importance of environmental wind shear in producing severe weather is recognized, a tendency persists to classify storms only by their reflectivity properties. Recent studies with Doppler radar observations sug gest that supercell features are determined in large part by their kinematic properties. Multicell and single-cell thunderstorms should possess weak vorticity. In supercells, updraft rotation hinders the across-storm translation of small-scale radar reflectivity and updraft elements. Instead, convective elements are swept to stagnation points upwind of the updraft mesocyclone where they eventually become indistinguishable from the background reflectivity and updraft. The distribution of helicity and pressure gradients determines the organization of turbulence within thunderstorms. The steadiness of supercells seems to lie with large but simple updraft structures that are characterized by laminar flow and are undiluted by mixing.

MESOSCALE CONVECTIVE SYSTEMS

Diagnosis of pressure and buoyancy fields in convective storms based upon velocity analyses from Doppler radar observations contributes to enhanced understanding of storm processes. In the recent past, pressure and buoyancy have been retrieved from isolated thunderstorms. A new effort has extended retrieval to diagnosis of these fields in mesoscale convective systems.

SEVERE THUNDERSTORM PHENOMENA

A (Beltrami) flow model, in which vorticity and velocity are everywhere parallel, is being used to provide insights into the pressure field around an axisymmetric rotating updraft. Although buoyancy is not included, this model is valuable because it has an exact analytical solution. Results explain how the surface mesolow can be several kilometers away from the updraft and circulation centers, and why mesocyclones have a characteristic size and rotation rate. This work is being extended to allow density to be a function of height.

The source of vertical helicity (the product of vertical velocity and vertical vorticity) in convective cells is being investigated, using theory and a three-dimensional numerical model. For dry convection, vertical helicity is produced from the transfer of environmental horizontal helicity (scalar product of horizontal vorticity and storm-relative horizontal velocity). There is no net buoyant production of vertical helicity.

Tornado windspeeds have been translated into structural loads, and these loads compared with strengths of some common and upgraded roof connections. Conclusions are that the strength of common connections intersects various windspeed probability curves in the steepest parts of these curves. This implies that slight changes in connection strength provide large changes in the structural reliability of the construction.

One channel of NSSL's Norman Doppler radar has been modified to achieve a large unambiguous velocity range (91 m s^{-1} making possible nonaliased velocity spectra for sample volumes that include tornadoes. From spectral skirts, the maximum sampled velocity components have been inferred as tornado windspeeds. For moderate tornado (F2 classification) in 1977, inferred wind speed was 65 m s^{-1} and for a violent tornado (F4) in 1981 inferred wind speed was 90 m s^{-1}. Doppler measurements are hampered by an aspect ratio problem between a radar beam whose size increases with range, versus a relatively small tornado target. These factors sometimes cause an underestimate of true maximum speeds.

A portable instrument, TOTO (Totable Tornado Observatory), designed at NSSL, makes direct measurements of meteorological variables in tornadoes. Wind speed and direction, temperature, and pressure have been measured near tornadoes and beneath a rotating wall cloud. Data from damage surveys and Doppler radar are used in conjunction with TOTO measurements to obtain estimates of wind speeds in and near tornadoes. Wind speed and pressure estimates from the latest data collection (the Ardmore, Oklahoma, tornado of 29 April 1985) are 30 m s^{-1} maximum tangential velocity and 5.5-mb pressure drop. The tornado was very weak as it passed over the device.

APPLICATIONS AND TECHNIQUE DEVELOPMENT

We developed a simple technique for estimating vorticity, divergence, and vertical velocity from single-Doppler velocity data that contain mesocyclone and divergence signatures. The technique has been applied to observations collected in the 2 May 1979 Lahoma, Oklahoma, tornadic storm and verified using vorticity and vertical velocity values obtained from dual Doppler analyses. Although magnitudes and vertical distribution of single-Doppler and mean dual-Doppler vertical velocity values differ, the patterns obtained from single-and dual-Doppler analyses are strikingly similar. Periods of vertical vorticity and vertical velocity intensification at low and middle levels are well depicted in the single-Doppler analysis.

Vertical velocities computed from multiple-Doppler radar measurements contain errors that exceed those expected on the basis of theoretical considerations. The nature and scope of these errors were investigated using actual data. Storm advection, incomplete sampling of low-altitude divergence caused by the radar horizon, top boundary errors, and uneven terrain were studied. All were dismissed as dominant sources of error for the case under consideration. A search for the cause of the errors continues because realistic vertical velocity adjustment schemes cannot be developed until the dominant source of the errors is discovered and understood.

We completed a study of growth rates of radar reflectivity and updraft speed using NEXRAD real-time computer algorithms to evaluate an interlaced scanning strategy. This sampling strategy provides updates of low-level information every 2 1/2 min and may be important for detecting rapidly developing hazardous phenomena such as microbursts in roughly one-half the time of the current proposed scanning strategy. This evaluation reveals that detectability of hazards is not significantly impaired by interlaced scanning.

Only about half of all observed mesocyclones are tornadic. A study was undertaken to address the problem of discriminating between tornadic and nontornadic mesocyclone types. The effort is based upon the premise that tornado formation is related to mesocyclone strength. This idea is examined through a parameter called Excess Rotational Kinetic Energy (ERKE), which represents the rotational kinetic energy of a mesocyclone after subtraction of energy corresponding to threshold mesocyclone shear. ERKE is a function of mesocyclone radius and rotational velocity, which are readily available from the Doppler velocity field, and so the parameter is suitable for real-time applications. Preliminary findings from an examination of 10 mesocyclones suggest that the magnitude and height distribution of ERKE distinguishes between mesocyclone types, and, if a mesocyclone is tornadic, gives an indication of upcoming tornado severity.

MICROPHYSICAL AND ELECTRICAL PROPERTIES OF THUNDERSTORMS

A one-dimensional cloud model using single-Doppler, aircraft, and balloon observations as input was used to study interrelationships among airflow, microphysics, and electrification in an isolated New Mexico mountain thunderstorm. The calculated rate of noninductive charge transfer accompanying collision and separation of ice crystals and riming graupel particles, which exceeds 10 C km^{-3} min^{-1}, is in direct proportion to cloud and precipitation content. Agreement of model calculations with balloon measurements of space charge density and the vertical electric field suggests that the noninductive mechanism accounts for a substantial portion of the storm's total separated charge. A major and

poorly understood process in cloud physics is the charging of thunderstorms. The significance of this study is the verification of calculation of cloud properties, radar reflectivity, charge separation, and electric field growth, using a comprehensive model-derived data set.

A microphysical retrieval sensitivity test demonstrated the critical dependence of microphysically retrieved precipitation and reflectivity fields on the detailed input wind field, and in particular the vertical velocity field. Improved quantification of wind analysis error sources, whose distribution influences the analyzed vertical velocities, holds the promise of significantly improved retrievals of dynamic and microphysical variables from cloud models that accept Doppler-derived airflow as their primary input.

Relationships among electrical activity, airflow, and microphysical properties in a severe Oklahoma thunderstorm that occurred on 19 June 1980 were documented. The most likely charge separation mechanisms, as inferred from a temporal and spatial correlation of derived and microphysically retrieved cloud properties with observed electrical activity, involve the rebounding collisions between ice particles at cloud temperatures below freezing.

RAWINSONDE DATA

Data processing and quality control continued on the Oklahoma-Kansas Preliminary Regional Experiment for Stormscale Operational and Research Meteorology (PRE–STORM) 1985 rawinsonde data set. Nearly 2,000 soundings were taken at supplemental and NWS network sites. There is considerable demand for the data in the research community, and research using the data is already beginning to appear in publications and at conferences.

Five supplemental rawinsonde sites were operated during the spring of 1986. Personnel and equipment were supported at four sites by USAF 6th Weather Squadron (mobile) from Hurlburt Field, Florida. A fifth site was operated by the U.S. Army Field Artillery Board from Fort Sill, Oklahoma. Between 4 April and 30 May 1986, 211 soundings were flown. Comparison flights were also made for the 50-MHz wind Profiler. Two soundings per day were made for 5 days at NSSL, using the new GMD 5 ground station developed for the Air Force. Several software problems were identified and reported.

Plans FY 1987

- A case study of Oklahoma-Kansas (OK)–PRE–STORM data sets capturing the central Kansas macroburst and colliding outflows on 23–24 June 1985 will continue. Emphasis is on understanding the macroburst and the surprising lack of convective development in the intense convergence zone along the associated outflow boundaries.

- A case study of the 12–13 May 1985 OK–PRE–STORM severe storms will examine destabilization mechanisms and investigate the use of OK–PRE–STORM Wind Profiler data in severe thunderstorm research.

- A study of 10–11 June 1985 PRE–STORM mesoscale convective system (MCS) is under way. The study will focus on the structure and orientation of convective updrafts along the leading edge of the MCS. A budget analysis of horizontal vorticity about the convective leading edge will be performed.

- The 2 May tornadic storm, the 6–7 May case, and the 12 May 1985 MCS formation studies will be completed.

- A comparison will be made to determine if the atmospheric features clearly detectable with the high-density observing network of OK–PRE–STORM are detectable with the low-density NWS observing network.

- Initial data editing has begun on a pair of merging severe hailstorms that occurred in central Oklahoma on the evening of 26 May 1985. Since both storms contained mesocyclones, it is anticipated that the completed study will help to improve our understanding of mesocyclone evolution.

- Analysis of pressure and velocity fields and the overall organization of the 19 May 1977 squall line will continue.

- The study of single-Doppler mesocyclone and divergence signatures on 2 May 1979 and comparison of results with dual-Doppler derived fields will continue. A formal publication will be prepared.

- Documentation of the Binger storm with respect to kinematics of an echo weak hole, microphysics deduced from vortex evolution, and storm dynamics will be completed and results submitted for publication.

- The relation between surface parameters and the erosion of boundary layer capping inversions will be investigated. The purpose is to provide better guidance to NWS forecasters during severe weather situations.

- A study of microphysical retrieval sensitivity to the variation of modeled microphysical processes in thunderstorms will be finalized. An extensive analysis of the relations of microphysical and electrical properties in the 19 June 1980 storm, using time-space wind analyses and the time-dependent solution of the cloud model, will be concluded.

- Study of the microphysical and electrical properties of the New Mexico mountain thunderstorms of 31 July 1984 will continue.

- A simplified numerical model is being developed for simulating the initiation and evolution of vorticity (mesocyclone) within severe thunderstorms. Vorticity is computed from the vorticity equation in which a constant environmental wind field and time-dependent kinematic and thermodynamic parameters within the storm are specified by analytical functions. The model will be used in conjunction with the study of the Agawam severe thunderstorm that occurred on 6 June 1979. This storm is one of the first within which the mesocyclone initiation process has been documented.

- Planning for NSSL's installation of a PROFS Operational Weather Education and Research (POWER) system during Spring 1987 will be completed. NSSL will work with PROFS in developing specifications of capabilities needed in a workstation designed primarily for research applications.

- A training manual on the interpretation of NEXRAD Doppler radar displays will be prepared.

- Documentation of the 1986 Spring Program will be completed.

- Winds and reflectivity fields from an analytical hurricane model are to be used for constructing simulated single-Doppler radar signatures for mature hurricanes. A formal publication describing the technique that produced the analytical fields of 3–D hurricane wind and reflectivity data will be prepared.

- The generation of 30 universal format Doppler radar data tapes containing reflectivity, radial velocity, and spectrum width values within a mature hurricane continues. The data tapes will be used for testing NEXRAD Doppler radar algorithms.

DOPPLER RADAR AND STORM ELECTRICITY RESEARCH

Accomplishments FY 1986

DOPPLER RADAR

Prestorm Environment and Storm Initiation

Model development continued with the goal of diagnosing short-term temperature and moisture changes aloft. The model is intended to help both researchers and forecasters to monitor stability changes associated with the moisture-capping inversion prior to possible thunderstorm development. The model updates initial temperature and moisture profiles measured by rawinsondes, using subsequent radar wind data and models for evaporation, sensible heating, and mixed layer growth. Comparison of the results with later soundings and total precipitable water measured by a vertically pointed radiometer indicates skill in the diagnosed soundings. Radar estimates of vertical air motion appear to have the most diagnostic value in the model.

Radar reflectivity in clear air has been observed to vary systematically with insolation, both during a solar eclipse and over the usual diurnal cycle. Observed reflectivity is considerably greater than expected from a mixed layer model for refractive index fluctuations. Also, the change in reflectivity is observed simultaneously above the mixed layer. We are continuing this research to understand the physical mechanisms responsible for observed reflectivity characteristics.

A single-Doppler analysis technique known as modified velocity volume processing (MVVP) was thoroughly tested. Of specific interest is the capability of the linear wind model to estimate horizontal velocity divergence. It was shown that the accuracy of the estimates depends on several factors. Very important is the geometry of the MVVP analysis volume, which plays an integral part in determining the magnitudes of bias and variance errors in the parameter estimates. For a properly designed analysis volume, the uncertainty in divergence due to velocity measurement errors was found to be on the order of 10^{-5} s^{-1}, nearly an order of magnitude less than the intensity of convergence usually significant for thunderstorm initiation. Bias, on the other hand, can be quite large ($\sim 10^{-4}$ s^{-1}) for typical values of second-order mesoscale wind variations.

Divergence fields were related to cloud and storm development as viewed on visible satellite images and radar reflectivity displays. The results of the MVVP analysis indicate the potential for using this technique as a short-term (1–2 h) forecast tool. For example, storms developed early in the prestorm data collection period within a broad area of analyzed convergence to the northwest of the radar. Given the magnitudes of the measured convergence and the required lifting that air parcels must undergo to reach their level of free convection, storm development in this region could be realized in 1–2 h. In regions of divergent winds, skies were generally cloud-free although small cumulus were present in the area to the southwest of the radar.

Wind Profilers

Work was initiated to examine OK–PRE–STORM wind Profiler data for consistency and for use in determining ageostrophic winds.

Comparisons were carried out between the wind fields observed by a 50-MHz radar and rawinsondes launched by the Weather Service Forecast Office in Oklahoma City. These comparisons helped identify and correct several hardware problems, so that the two instruments' measurements agreed reasonably well. An attempt was made to calibrate the radar with sun radiation, but other interferences precluded precise measurement. However, the antenna-pointing directions were verified with measurements of noise from the galactic plane.

The procedure to track balloons with a Doppler weather radar was modified. We successfully tested the modifications and were able to track a balloon automatically from about 1 km above ground

until it burst at above 10 km. The agreement between radar winds and rawinsonde winds obtained from that same balloon was extremely good (rms error less than 1 m s^{-1}).

Downdrafts and Gust Fronts

Study of downdrafts (downbursts) produced by severe storms and squall lines in Oklahoma was completed. Often these outflows are asymmetric, generate strong shears, and are accompanied by heavy rain and/or hail. Such conditions present potential hazards to aviation, but the apparent intensity provides warning so that aircraft would not penetrate the cell. On the other hand, summer downbursts produced by small explosive cells may be difficult to detect and predict; their intensity may not preclude aircraft penetration, yet the shears produced by them can be lethal if encountered by aircraft on the approach path. We have been engaged in a modest data-gathering effort to supplement our knowledge of such summertime microbursts. Data collection was successful in that several microbursts were observed in a tropical air mass with our two Doppler radars. Preliminary examination of the data indicates that convergence aloft (2.5 km above ground) preceded by several minutes the outflow near the ground.

Solitary Wave Research

Examination of microbarograph records revealed that a substantial number of solitary waves occurred in central Oklahoma in May and June of 1985 during the OK–PRE–STORM observational period. Examination of radar records has begun, to determine which of these waves were also recorded by the radars.

Progress has been made in the theoretical analysis of wave parameters for some specific vertical profiles of potential temperature and wind shear that have been observed to support solitary wave propagation. Solutions for nonlinear waves above the inversion layer were derived, and equations incorporating wind shear were developed.

Radar, surface, and tower observations revealed the wave-like nature of the leading edge of one thunderstorm cold outflow that was moving in a stably stratified lower atmosphere. Three distinct waves, spaced 12 km apart, were detected at the front and within the leading portion of the gravity current. The leading wave had the largest amplitude, and the amplitudes decreased thereafter. These wave disturbances were generated by the density current intrusion, and they eventually propagated ahead of the current within the continuously stratified ambient environment in a manner similar to that simulated by others in laboratories. These waves resemble solitary and internal undular bore waves. The uniqueness of this data set lies in the fact that observations were collected during the early, formative stages, when the waves had not yet completely separated from the gravity current.

Turbulence

After an extensive search of NSSL's dual-Doppler radar data files we found eight volume scans containing valid spectral width data for the same time from both the Norman and Cimarron Doppler radars. Although the data base is limited, comparisons of spectral widths from the two radars suggest that storm turbulence is isotropic on scales less than the radars' resolution volume (~ 1 km). Spectral widths agree to within 2 m s^{-1} with about a 90% confidence.

Hail Detection

A study of hail signatures was conducted. The study was based on our observation that strong reflectivity cores may be involved in a three-body scattering such that the microwave energy scattered by hail is reflected from the ground back to the hail and then to the radar. Observed reflectivities and velocities follow expected theoretical profiles remarkably well.

Further studies on the relationship between parameters that measure storm top divergent outflow magnitude and maximum hailstone diameters continued with analysis of 49 cases. For the best measurement techniques, the results showed correlation coefficients of 0.8 to 0.9.

Polarization Studies

First measurements of differential propagation phase shift constant K_{DP} were provided by NSSL's dual polarized radar. Programs were developed to estimate K_{DP} from the time series records and to generate color displays of K_{DP}. A comparative analysis of the rainfall rate (R) calculated using Z, R, Z_{DR},R and K_{DP},R relationships has indicated that the K_{DP},R relationship is most useful at higher reflectivities (>45 dBZ). The estimated rain rates from polarization measurements are higher than rates from a Z,R relationship. It appears that drops are more oblate than equilibrium shapes. Also at lower reflectivities (<30 dBZ) the spread of K_{DP} and Z_{DR} is larger than predictions based on statistical uncertainty. We are looking to see which combinations of Z_{DR} and Z_H (e.g., high Z, low Z_{DR}) might indicate the presence of hail, and whether K_{DP} data can be used to evaluate hail dimension.

During the spring of 1986 several polarization measurements were conducted in rain and hail storms while a disdrometer collected data on drop size distributions.

A theoretical analysis was performed to determine optimum signal transmission and processing scheme so that both polarization and Doppler measurements can be obtained in minimum time. So far the best approach consists of an alternating transmission sequence of horizontally and vertically polarized electric fields. Doppler velocities are computed after the propagation phase shift has been isolated from the autocovariance at lag one of the echoes.

Algorithms for Next-Generation Weather Radar (NEXRAD)

We further refined and tested several NEXRAD algorithms. The gust front algorithm was improved and expanded on the basis of past analyses. We compared algorithm outputs based on data from our two radars that viewed the same gust front. The locations of the gust front agreed to within 1 km. Agreement was similarly favorable between gust front positions inferred from surface station data and obtained with the algorithm. We also incorporated into the algorithm tracking in rectangular coordinates, a vertical continuity requirement, and a uniform wind analysis on either side of the front. The algorithm was transferred to MIT's Lincoln Laboratory and first used in real time in the Cooperative Huntsville Meteorological Experiment (COHMEX) in Huntsville, Alabama.

An algorithm to detect tornadic vortex signatures and an algorithm to characterize storm severity from divergence measurements were documented in reports to the NEXRAD Joint System Program Office.

Enhancement and Analysis of Observing Capabilities

A NASA-supported project to estimate errors in wind fields measured by air borne Doppler lidar was conducted. Aircraft position data obtained from INS, LORAN-C, and nadir photos were computer-processed for comparison.

Experimental and computational procedures were developed for real-time analysis of wind fields last spring. Sounding evolution analysis and VAD analysis were conducted on selected days, prior to storm formation.

Construction and testing of a prototype eight-element pattern-switching antenna array was completed. Pattern measurements carried out in an anechoic chamber (courtesy of FAA in Oklahoma City) demonstrated the feasibility of a pattern-switching concept for sidelobe signal suppression in pulsed-Doppler radars.

Analysis of a ground clutter canceling scheme on a staggered pulse train was completed. We found that a finite impulse response filter based on a window approach cancels the DC component. Its notch also appears at several locations in the extended unambiguous velocity interval; this must be accounted for when filtered velocity data are interpreted.

STORM ELECTRICITY

National Plan for Lightning Data

We participated in the writing of a report on the status of national programs for lightning detection systems, issued by the Federal Coordinator for Meteorological Services and Supporting Research. A test that NSSL is conducting forms the cornerstone of the Government's evaluation of systems for detecting and locating lightning ground strikes. The results of this test will affect decisions on systems and data bases to be used by NWS and other Federal agencies.

NOAA Needs for Lightning Research

The Storm Electricity Group, in collaboration with ERL's Weather Research Program, developed part of a NOAA-wide identification of lightning research needs. Needs were identified in NWS, NESDIS, and ERL. An important aspect of the report is that it formed NOAA's input to NASA on potential uses of data that could be provided by a lightning mapper carried on a geosynchronous satellite. Needs in the area of lightning data for identification, forecasting, and/or warning included research concerning (1) direct thunderstorm identification with objective data, (2) precipitation and flash floods, (3) severe storms, (4) mesoscale convective systems, (5) aviation hazards, and (6) thunderstorms over oceans, mountains, or in ground clutter. Other NOAA operational needs are verification of forecasts and warnings and a national ground strike climatology. Specific NOAA research applications were found to be (1) storm severity, (2) mesoscale convective systems, (3) atmospheric chemistry studies and modeling, (4) electrical and microphysical interactions, (5) modeling using climatological parameters, (6) associated and long-path-length lightning, (7) relationships among storm dynamics, precipitation, and lightning, and (8) lightning frequency in thunderstorm forecasts.

Several of these needs can be served only by the full-disk and continuous mapping of all lightning flashes. Our report and subsequent meetings between NOAA and NASA resulted in NASA's approval of placement of a mapper on a GOES-series satellite. Included in the approval are the removal of space and power constraints that could have compromised NOAA research on the satellite. Indications now are that we can realistically expect to have a new and valuable research sensor, with several potential applications for NOAA.

Many of these same needs were also incorporated in the National Plan for Lightning Data.

Lightning and Vertical Reflectivity Structure

Radars with 10-cm and 70-cm wavelength were used to determine the vertical precipitation structure and lightning activity, respectively, in a multicell thunderstorm during 1.5 h of continuous observations. In all six cells of the storm, vertical growth was about 3 times faster than decay. All cells had lower flash density centers at 7 km that produced up to 32 flashes $m^{-1}km^{-1}$. We found a positive correlation between the maximum flash density and the heights of both the 40- and 50-dBZ cores. We found the following repetitive patterns in reflectivity and lightning in all six cells: (1) During the initial rapid growth of a cell, lightning is concentrated on the leading edge of the 50-dBZ core of the cell and between this cell and the dissipating neighboring cell, and (2) in the decaying stage of a cell, lightning activity spreads farther into the cell's main reflectivity core.

Participation in COHMEX

We were asked to participate in COHMEX under the SPACE (Satellite Precipitation and Cloud Experiment) portion of the program. Our three major collaborative experiments required intercepting storms with NSSL's mobile laboratory, to (1) acquire electrical data to be used to study the interaction between electricity and cloud microphysics and dynamics, (2) acquire ground truth lightning data to be compared with observations made above the same storm with a NASA U2 aircraft (as part of our ongoing role in the satellite lightning mapper project), (3) do mobile ballooning in collaboration with the University of Mississippi to measure the electric field vector, temperature, and pressure within storms.

We were able to adapt storm intercept techniques used on the Great Plains to intercept a large percentage of targeted storms within the mountainous research area. Highlights of our data collection include (1) complete life cycle of an isolated storm cell, documented with dual-polarized radar and ground-based electrical measurements; (2) data from coordinated acquisition with instrumented airplanes during several storms; (3) storm-environment electrical and meteorological soundings from more than a dozen mobile balloons; and (4) observations showing a fascinating and probably significant correlation between changes in echoes from dual-polarized radar and the onset of lightning.

One balloon flight of interest entered a long-lived storm during its initial development and remained in the storm. We recorded electric fields from within the storm during its lifetime of about 4 h, as we tracked the storm for about 100 km. This case has been selected as the primary analysis candidate in SPACE. We were also able to provide other scientists in COHMEX with qualitative data on wind speed and direction for several downburst events in the storm.

Other scientific benefits of participation in COHMEX include measurements of Maxwell currents beneath storms, obtained with NSSL's mobile lab in collaboration with the University of Arizona. Maxwell current is hypothesized to be a measure of the thunderstorm generator, and to have implications extending from individual cells to the global circuit.

Finally, we demonstrated the utility of the mobile ballooning concept to make new measurements in NSSL's planned studies of severe storm microphysics with dual-polarized radar.

Radar Antenna Sidelobe Effects on Observations of Lightning

As part of the study of lightning and storm structure, we analyzed the effect of echoes received in antenna sidelobes (since lightning is an intense target). By using radar cross-section discrimination, we concluded that the distribution of lightning within storms as obtained with radar depicts reliably the location of the flash activity maxima and the trends with time.

Lightning Hazards to Aviation

NSSL has continued to represent NOAA on the National Interagency Coordinating Group (NICG) of the Atmospheric Electricity Hazards Protection Progam. NSSL received the Group's annual award in 1986 for significant contributions to basic research on lightning hazards and for NSSL's contribution to the success of the NASA Hazards to Aviation Program. As part of our continued participation in the NICG, we are organizing the 1988 International Aerospace and Ground Conference on Lightning and Static Electricity, which we will chair.

Our analysis of lightning strikes to the NASA F106–B shows that the majority of direct strikes to the airplane at low altitudes (6–8 km) occurred during the decaying stage of storm cell evolution. All strikes to the F106–B associated with cloud-to-ground flashes were intracloud portions of the discharge, not the return stroke channels that may represent a more severe threat to aircraft. As for higher altitudes, the probability of aircraft being struck was found to increase as the natural occurrence of lightning decreases.

Lightning and Mesocyclone Evolution

We continue to find evidence that the intracloud lightning rate is directly tied to severe storm evolution; in particular, the intracloud rate is higher when the mesocyclone is intensifying and at peak strength aloft. We have also found this same correlation with the existence of high reflectivity aloft. In contrast, ground flashes reach their maximum rate after dissipation of the mesocyclone and any tornadic activity. Thus both intracloud and cloud-to-ground lightning need to be evaluated for possible inclusion in forecast and warning applications. The lack of widespread and routine acquisition of intracloud flash data has been noted in other sections; significant and rapid progress on these problems awaits data from the satellite-borne lightning mapper system.

Evaluation of Strike-Locating Systems

We are evaluating two networks of commercial devices for locating lightning ground strikes, to determine detection efficiency and accuracy. We are also comparing results of one of the networks

with a single-station thunderstorm sensor manufactured by the same company. This evaluation is being done for the Office of the Federal Coordinator for Meteorological Services and Supporting Research. One network is a time-of-arrival system; the other is a direction-finder system. Results from the two networks will be compared with "ground truth" data from three sets of instrumentation: (1) an all-azimuth television (TV) system at NSSL, (2) an all-azimuth TV system at Tulsa International Airport, and (3) two TV cameras mounted on remotely steerable pan-tilt units on NSSL's mobile laboratory. In addition to video data, extremely-low-frequency electric field signals will be recorded to determine whether detection of positive ground flashes by the two networks are false. Analysis of these systems will continue into next year.

Studies completed this year show that the direction finder system produces false detections no more than 10% of the time, and that they occur only with flashes having the lowest radiation signal amplitudes. We also completed a study of the Oklahoma portion of our system. We found that random errors in the direction of lightning strikes from each station are 1°–2°, and flash detection efficiency is typically 70%.

Measurements of Lightning Return-Stroke Velocities

We improved the response of our system developed last year to measure the speed of propagation of channels between the ground and the cloud by using eight silicon detectors behind horizontal slits in the focal plane of a lens on a camera body. The device and a TV camera to record channel geometry are installed in an environmental enclosure atop the mobile laboratory, allowing channel geometry, and subsequently two-dimensional velocity, to be recorded for the first time while the laboratory is moving. Analysis plans call for calculation of velocities and determination of their relationship with electric field change wave forms for lightning in Oklahoma and Alabama (during COHMEX), and for ground flashes triggered at Kennedy Space Center. Knowledge of channel velocity is important in basic physics studies and in modeling peak currents.

Comparison of Lightning Strikes to Aircraft in Thunderstorms With Intracloud Flashes

Observations of lightning strikes to the NASA F106–B research airplane were used to infer properties of naturally occurring intracloud flashes. Data analyzed included airborne measurements of currents flowing through the nose and tail fin cap of the airplane, electric field derivatives, transient light changes, TV recordings of lightning strikes, and radar echoes of lightning. We found that strike development usually consists of an initiation period having rapid current pulses at rates up to $10^4\ s^{-1}$ for less than 3 ms, followed by continuous current of tens of amperes lasting up to 400 ms. During the continuous-current period, pulses resembling previously documented intracloud return surges were documented.

Quasi-Stable Lightning

Analysis was completed on unusual and rapidly occurring electrical discharges that were recorded by radar in an active thunderstorm. The maximum rate of these discharges was 200 per minute; average duration was only about 13 ms. The discharges have been defined by us as "quasi-stable" and are hypothesized to be different from a fully developed flash in that they do not propagate outside their initiation volume. This suggests that the region where lightning begins is only tens to hundreds of meters across. This phenomenon seems similar to the high intracloud lightning we first documented a few years ago. Results of this study may apply to aircraft operations inside clouds.

Cloud Electricity Measurement Techniques

We completed for inclusion in the forthcoming edition of *The Thunderstorm* a chapter on techniques for measuring electrical parameters within the thunderstorm environment. This work contains sufficient detail to provide understanding of various instruments and their proper use. The compilation, the only known collection describing modern techniques, also includes an analysis of optimal site selection for mounting electric field mills on airplanes.

Facilities; Instruments

An improved antenna design and a new site at Mustang, Oklahoma, were selected for our unique VHF system to replace the present one at Page Field. More flashes will be mapped with higher detail in the future.

Our mobile laboratory was replaced as planned by instrumenting a van (15-passenger) with a 4-kW 110-V AC generator, electric field sensors, optical detectors, two remotely controlled pan-tilt units with azimuth position readouts for the TV cameras atop the lab, a 14-channel wide-bandwidth tape recorder, a LORAN-C navigation receiver for position location, and provisions for meteorological sensors and balloon telemetry receiving equipment.

Plans FY 1987

DOPPLER RADAR

- To develop improved operational capabilities for forecasting the locations and intensities of storms, we shall continue in-depth examinations of preconvective radar data relative to data from other sources and to theory. An effort will be made to diagnose, in real time, changes in stability and convergence of the lower atmosphere from Doppler radar data.
- The wind-profiling capability of weather radars will be examined both theoretically and experimentally. The accuracy of the 50-MHz wind Profiler will be evaluated, and examination of wind Profiler data from the OK-PRE-STORM experiment will begin.
- To predict downdrafts and gust fronts, study of their origin and evolu tion will continue. An attempt will be made to collect data on downbursts in summer storms, the kind that have been implicated in aircraft accidents.
- A joint NSSL/Australian National University analysis of solitary wave data will continue.
- We shall continue to analyze polarization data from the 1985 and 1986 spring experiments to determine the quality of rain rate estimates and assess the capability to identify hydrometeors remotely in storms. Disdrometer data collected in the spring of 1986 will be used to derive drop size distributions and rain rates. These will be compared with results from polarization measurements.
- NEXRAD algorithms for detection and tracking of hazardous weather will be improved.

STORM ELECTRICITY

- Consult and perform research with other NOAA groups to develop uses of ground and satellite-based lightning data.
- Study lightning and vertical storm structure to detail their effects on cloud microphysics.
- Analyze COHMEX data, especially data for storms studied with multiple Doppler and dual-polarized radars, and through which we flew electric field soundings.
- Analyze the physical characteristics of positive cloud-to-ground flashes.
- Analyze additional tornadic storm case studies to determine relationships among intracloud flashes, ground flashes, high reflectivity, and development of cyclonic shear in the mesocyclone.

- Complete data analyses and prepare the initial evaluation document for two lightning ground strike locating systems.
- Determine return stroke velocities from lightning data obtained on the Great Plains, during COHMEX, and from rocket-triggered flashes at Kennedy Space Center, and evaluate instrumentation for obtaining such measurements.
- Complete analysis of the characteristics of lightning strikes to the NASA F106–B aircraft, to infer properties of naturally occurring intracloud flashes.
- Upgrade NSSL's VHF lightning-mapping system by improving antenna systems, moving one site, upgrading the real-time data display, and moving the electronics into more permanent buildings.
- Improve instrumentation in our mobile laboratory to better support DOPLIGHT–87, and begin to fabricate a mobile balloon launching and tracking system.
- Provide ground truth data for algorithm verification, as part of DOPLIGHT–87.
- Perform initial analysis of long-term lightning effects on precipitation and on the reorientation of hydrometeors by lightning.

COMPUTER AND ENGINEERING SUPPORT AND DEVELOPMENT

Accomplishments FY 1986

COMPUTING AND DATA PROCESSING

The NSSL VAX 11/780 was upgraded to include a seven-track tape drive.

A PROFS workstation was lent to NSSL for the 1986 Spring Program. The system consisted of a DEC Micro-VAX II with a RAMTEK 9465 color graphics display. Data were supplied over a 56,000-baud leased line from Boulder, Colorado. The workstation was used during the summer to identify function requirements for a research workstation.

The MICOM telecommunication system continued to grow with the addition of several terminals. Use of the electronic switch to access the CDC 855/205 in Gaithersburg continues to increase.

Fiber optic cables interconnecting the main NSSL building to external buildings were installed and hardware for multiplexing was reviewed.

FACILITIES ENGINEERING

New Telephone System

A modern telephone system was installed at NSSL. Two features of the system are a private number to each phone location, and a detailed record of outgoing calls.

Data Acquisition Programs

NSSL Doppler radars were maintained operational during the period January through March to support a Winter Storm data acquisition program. From 1 April to 10 June, Doppler radars and the Stationary Automated Mesonetwork (SAM) stations were operated to support multiple research programs.

Doppler Radar Data to WSFO (DOPLIGHT)

During the Spring 1986 operation period (approximately 1 April to 10 June) Doppler radar and lightning data were transferred routinely to the Oklahoma City Weather Service Forecast Office (OKC

WSFO) at Will Rogers Field. These data proved useful to the duty forecaster and provided an additional opportunity for technology transfer and examination of Doppler and lightning data products. The OKC WSFO also sent the data to local television stations for selective broadcast.

Dual Polarization

Dual-polarization data were collected routinely with the Cimarron Doppler radar. Data have been utilized for hail and disdrometer raindrop measurements, aircraft penetration, cloud water content measurements, and various engineering evaluation and propagation studies.

Doppler-Balloon Project

The DOPLOON program successfully examined the feasibility of upper-air wind measurement by Doppler radar balloon tracking. Software was developed to allow automated computer control of the Norman Doppler antenna. Ten flights were made. Simultaneous radar-tracking and rawinsonde-derived wind data were found to be highly correlated. It was demonstrated that radar balloon tracking provides a valid measure of upper-level winds and that the technique is practical on an NSSL-type Doppler radar.

KTVY Tower

The KTVY tower data collection system was operated to support meteorological research. Real-time data were transmitted to Norman and into the VAX computer. Specific real-time data display products were developed.

Vertically Pointing Radar

We designed a system to share the radar transmitter with a separate vertically pointing antenna and receiver. Hardware components were purchased, and component testing began.

FACILITIES DEVELOPMENT

- Cimarron radar. A nine-track recorder system was commissioned. A radar preprocessor, a Genesco color display generator, and three new color monitors were designed and installed.

- Norman radar. A microcomputer was interfaced to the radar data acquisition and antenna control equipment. It allows interactive microcomputer control of both antenna and data collection. The system was used to support the Winter Storm and Spring Programs.

- 405-MHz Profiler antenna. Components were received, assembled, and tested. The antenna and drive system are fully operational. Final evaluation of the system awaits arrival of the transmitter/receiver and data processing components.

- Fiber optics link. During FY 1986, a study was made to determine the best approach to solve the real-time data transmission problems. Fiber optic technology was chosen as the best alternative. Fiber optic cable was installed between the NSSL North Base facilities, and initial testing is complete.

- Microwave data link. System hardware for the microwave link was delivered and tested.

- Radar preprocessor. A radar preprocessor and real-time color display system was designed and successfully deployed at the Cimarron Doppler facility.

PLANS FY 1987

COMPUTING AND DATA PROCESSING

The National Center for Atmospheric Research (NCAR) radar graphics editing system will be implemented on the NSSL VAX, and supplemental programs for using the universal format will be

added to in support both the graphics workstation and data analysis performed on the CDC 855. A visual Doppler editor will be implemented on the VAX and integrated into the NSSL version of the NCAR editor.

The hardware and software to create an interactive research workstation will be purchased and networked to the NSSL VAX.

Other upgrades to the VAX 11/780 will include the installation of an electrostatic plotter, a laser printer, and increased disk storage.

In cooperation with the University of Oklahoma, a DECNET link will be established between the NSSL and OU Geosciences VAXs to allow NSSL co-investigators access to the NSF supercomputer network.

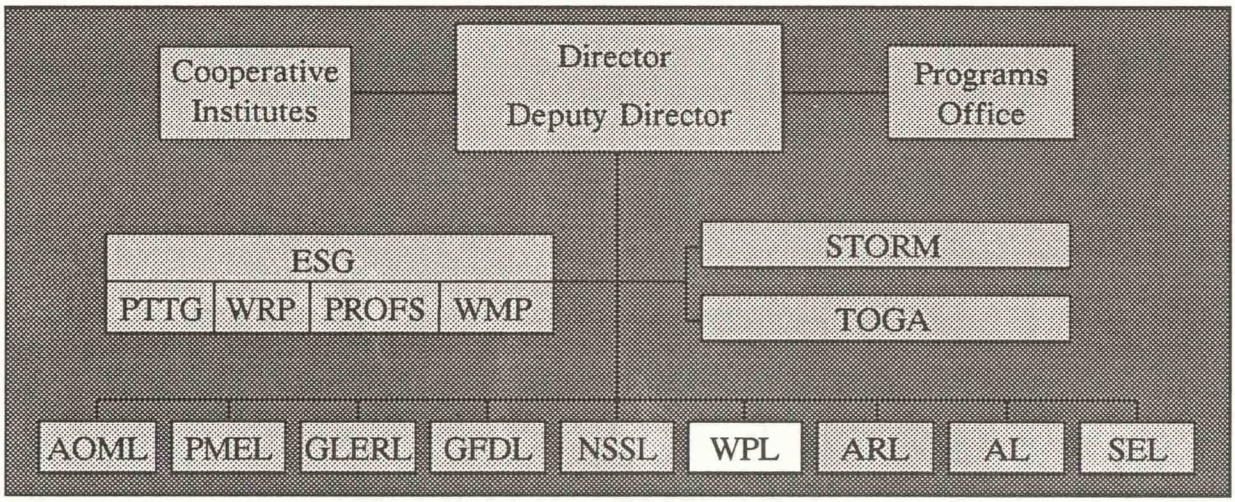
FACILITIES ENGINEERING

- We will emphasize transfer of operational Doppler radar products to the Oklahoma City WSFO. We will establish an even closer working relationship in both data exchange and applied research when the WSFO locates adjacent to NSSL in Winter 1986–87.

- Dual polarization has a demonstrated potential in meteorological research. It will be evaluated with respect to the NSSL meteorological research mission and NSSL priorities. Further engineering development will be initiated to support areas pertinent to the NSSL mission.

- Facilities engineering plans include completion of a 405-MHz wind Profiler, operation of an existing 50-MHz wind Profiler, establishment of a wideband data communication link between NSSL's Cimarron and Norman Doppler radars, development of a meteorological surface station for colocation with the demonstrated Network Wind Profilers, an engineering feasibility study of deployable upper-air sounding facilities, and expansion to a 48-fiber fiber optics data communication system for data exchange between NSSL and the new OKC WSFO.

- NSSL will continue to provide engineering and computer support to the NEXRAD Interim Operational Test Facility.



WAVE PROPAGATION LABORATORY
Boulder, Colorado
C. Gordon Little, Director

NOAA's core mission of atmospheric and oceanic forecasts and warnings requires that it observe the present states of the atmosphere and ocean in order to be able to predict their future states. Since both media are three-dimensional, the observations must also be three-dimensional; moreover, the data sets must adequately resolve spatial or temporal structures at least as small as those to be forecast.

In general, the denser the observational data set in space and time, the more complete and accurate the services can be. Experience has shown that in situ measurement methods, which require a sensor at each measurement location, are too expensive to be practical for anything but the largest scale phenomena. In 1967, the Wave Propagation Laboratory (WPL) was set up to explore the possibility that remote sensors might provide the several-orders-of-magnitude improvement in space/time density of observations required to predict or warn of smaller scale phenomena.

In summary, then, the WPL mission is to improve the Nation's geophysical research and services through the development, demonstration, and dissemination of cost-effective remote measurement systems. To achieve this goal, WPL must successfully perform the following functions:

- Detailed theoretical and experimental studies of the interactions of acoustic and electromagnetic waves with the atmosphere or ocean, with particular reference to the use of such interactions for remote-sensing purposes.

- Development and experimental evaluation of new geophysical remote-sensing concepts and systems.

- Application of the unique advantages of newly developed remote-sensing techniques to atmospheric and oceanic research.

- Improvement of the Nation's atmospheric and oceanic research, and forecasting and warning services, through transfer of remote-sensing technology to others.

Because observational capability underlies essentially all geophysical research and services, WPL's research has broad impact. The following presentations give a brief rationale for the research programs, and summarize the FY–1986 programs and FY–1987 plans. Where appropriate, the research tasks within each program are grouped according to meteorological scale.

WEATHER OBSERVATION AND PREDICTION

WPL's contributions to weather observation and prediction support NOAA's largest and most important single service, namely, weather forecasts and warnings. Such services are required on many space and time scales. WPL's remote-sensing R&D program includes contributions on all scales from the micrometeorological to the global.

MICROMETEOROLOGICAL R&D

Research on micrometeorological processes in the atmospheric boundary layer is important because these processes include the turbulent fluxes of heat, moisture, and momentum that change the dynamic and thermodynamic properties of air masses. Remote sensors contribute uniquely to the research by providing the resolution and continuity in both space and time that are required to observe, monitor, understand, and predict these important boundary layer processes. WPL has long led in the development and application of such sensors.

Accomplishments FY 1986

SENSOR DEVELOPMENT

Several new designs for an omnidirectional pressure probe were tested for pressure fluctuation measurements in the atmospheric boundary layer. A design showing particular promise has been chosen for further refinement and testing.

Previous measurements of entrainment into clouds have used chaff reflectivity to trace the chaff into precipitating convective clouds. A deficiency of this technique, the obscuring of the chaff signal by the cloud reflectivity, has been greatly reduced by the measurement of chaff circular depolarization ratio with a polarization diversity radar. This new technique permits the chaff to be observed long after its reflectivity signature has been lost in the cloud echo.

Analysis continued on the Flatville data set to relate millimeter wave and optical scintillation data to simultaneous meteorological data. We successfully performed and documented a preliminary test of path-averaged heat and moisture flux measurement techniques using these data. We have refined our ability to make path-averaged measurements of turbulence microscale, and hence momentum flux, on 600-m atmospheric paths.

In connection with our high-resolution, vertical profiling of turbulence parameters using an aircraft-to-ground propagation path, we published the theory of the concept and performed horizontal path tests during FY 1986. This work could have a significant effect on the understanding and even the prediction of outages of clear air radar echoes at different radar wavelengths.

Working with NOS, we tested two concepts for rapid precision leveling. A new surveying concept would allow longer path measurements of elevation, thereby dramatically reducing the amount of time needed to complete a survey.

We used data collected at the BAO by an FM–CW radar to evaluate the effect of nonuniform layering of refractive index fluctuations on the estimation of the scattering centroid location. The uncertainty in the location of the centroid has important implications to the accuracy of the determination of the height of wind measurements with wind-profiling radars.

RESEARCH

Fundamental experimental research on optical propagation in strong turbulence showed the existence of unexpectedly small fine-scale structure in the scintillation pattern.

Existing safety standards to prevent eye injury by lasers take no account of atmospheric scintillation phenomena. A new model of eye damage vs. exposure shows the need for a much larger safety margin.

An optical wind and refractive index meter is on loan to CSIRO Canberra in connection with work on measurement of evaporative flux.

BAO tower data were used to establish a relationship between static stability, temperature variance, and velocity fluctuations, leading to the possibility of estimating static stability aloft with acoustic techniques.

An investigation of the spectrum of wind fluctuations observed from a moving frame of reference, using the Doppler lidar in a continuous-wave mode, showed that considerably more energy was present at high frequencies when the observation point was translating. These results are important for modeling the effects of wind fluctuations on rotating wind turbine blades.

Plans FY 1987

SENSOR DEVELOPMENT

Upgrading of the two 3-cm- and single 8.6-mm-wavelength radars will continue with the installation of color displays, new high speed data acquisition systems, and video cameras. The quality of 3.2-cm Doppler polarization data will be improved by a realignment of the subreflector.

The omnidirectional pressure probe for boundary layer pressure fluctuation measurements will be field tested to determine its usefulness in detecting microburst signatures and in evaluating terms in the turbulent kinetic energy budget.

An experiment will be conducted at the BAO to determine the errors incurred in the measurement of variances and fluxes with a four-axis Doppler sodar system.

The observation of optical beam scintillation in strong turbulence will continue with a view to developing new atmospheric remote sensors.

RESEARCH

Entrainment studies using chaff and polarization diversity radars will continue.

The Flatville, Illinois, millimeter wave data set will be analyzed to look for propagation phenomena to exploit in the development of new remote sensors of bulk-meteorological and turbulent atmospheric parameters.

An attempt will be made to develop a theoretical or quasi-empirical relationship between shear and velocity variance in the lower atmosphere. This could help improve the reliability of velocity variance measurements made with WPL Profilers.

R&D ON MESO-BETA AND -GAMMA SCALES

A single ground-based scanning radar or lidar system can remotely monitor atmospheric processes on the meso-gamma (2 to 20 km) and perhaps the meso-beta (20 to 200 km) scales. Such data sets are required for an extraordinarily wide range of atmospheric research problems, as well as for short-term local weather nowcasts and forecasts. WPL activities relating to these scales that are assigned to the Weather Observing and Prediction program are divided into two main categories: mesoscale sensor

development, and mesoscale research. Specific applications of WPL's mesoscale remote sensors to air pollution studies are discussed in the section on Air Quality.

Accomplishments FY 1986

MESOSCALE SENSOR DEVELOPMENT

A new state-of-the-art laser transceiver was installed in the WPL pulsed-Doppler lidar system. The new lidar can produce 2 J of energy per pulse at a 50-Hz repetition rate. As part of the installation, significant thermal upgrades were made to the trailer housing the system, to improve long-term frequency stability.

Preliminary performance tests with the new Doppler lidar system indicated that the system sensitivity is somewhat less than anticipated. To investigate this discrepancy, a computer model was developed to simulate the optical field within the laser cavity. Several potential design modifications were identified for implementation in FY 1987 to improve system performance.

Techniques were developed to characterize the quantum efficiency of infrared detectors operating in an optical heterodyne mode. Exact characterization of detector quantum efficiency will improve the accuracy of atmospheric back-scatter measurements made with the pulsed coherent lidar.

Several aspects associated with the signal processing of aerosol-backscattered Doppler lidar signals were investigated. The poly-pulse-pair frequency estimation algorithm used in the coherent lidar system was found to produce better estimates in general than the commonly used complex covariance algorithm at low signal-to-noise ratio. A method for predicting the performance of a frequency estimator, based on the spectral peak, was developed and used to estimate errors in continuous-wave Doppler lidar velocity analyses. Applications of Kalman filtering for smoothing time series of coherent lidar velocity and intensity estimates from the turbulent atmosphere were studied, and found to produce good rejection of statistical noise.

Determination of water vapor flux was achieved by combining vertical profiles of horizontal velocity, measured by an 8.6-mm Doppler radar, with profiles of water vapor, measured from a dual-channel radiometer. These results, obtained during a weather modification experiment near Beaver, Utah, demonstrated a powerful new technique for monitoring the flow of atmospheric moisture.

RESEARCH ON MESO-BETA AND -GAMMA SCALES

Analysis of two case studies of the 1985 dryline experiment in Texas demonstrated the use of ground-based Doppler lidars in documenting gravity current, meso-beta (approximately 1 km) circulations at the leading edge of northward surges of the Texas dryline. Vertical motions in excess of 2 m s^{-1}, initiating severe mesoscale convective activity, were measured at the dryline head.

The structure of the vertical velocity field in and above the convective boundary layer was also determined through analysis of lidar returns. The spectra of velocity fluctuations were characterized by a classical Kolmogorov −5/3 slope in the boundary layer; fluctuations were of much smaller magnitude in the free atmosphere. Preliminary analysis also indicated that boundary layer rolls were present during the measurement period.

The Doppler lidar was used during the Meso-Gamma '86 experiment, marking the first field application of the upgraded transceiver. Several significant downburst/microburst events were recorded during the 3-month experiment. The lidar performed very reliably, firing several million shots without significant downtime. Lidar data acquisition provided real-time display of the progression of observed events. Microbursts and gust fronts were also observed by WPL's dual-Doppler 3-cm radars during this field program.

A wind field analysis of a microburst obtained with the two WPL 3.2-cm Doppler radars suggested the possibility that divergent flow aloft might precede dangerous wind shears at the surface by several minutes.

The analyses of data from aircraft, radiosondes, and surface mesonet data collected during the Meso-Gamma '85 experiment have been completed. On the basis of the results it was possible to refine Wilczak's Front Range mesoscale model so that both cyclonic and anticyclonic circulations are successfully simulated with one set of parameters. Another important outcome of this study was the establishment of a Froude number criterion that shows a clear demarcation between conditions that lead or do not lead to the development of a Denver cyclone. This criterion can be used as a predictive tool for forecasting the occurrence of a cyclone.

We completed a study showing the relationship between intensity and location of severe weather and infrasound signals observed at ranges of several kilometers to several hundred kilometers.

The WPL Doppler radars were successfully used in a study of air motions in the marine boundary layer over the Santa Barbara Channel. The existence of a 30-km-diameter closed circulation, resulting from curvature around nearby mountainous terrain interacting with drainage flows, was confirmed by these observations.

Radiometric observations of the short-term variability of geopotential heights and thicknesses were made during the passage of a cold front and during a well-documented gravity wave event. Both time series and spectra showed excellent agreement with independent information. Studies are under way, in collaboration with Georgia Institute of Technology, to compare observed features of the gravity wave event with characteristics predicted from a wave model.

An analysis of remote-sensing data from Beaver, Utah, indicated that there was a positive correlation between water vapor flux and amounts of liquid water when data were obtained on time scales of several hours. Maxima in vapor flux preceded peaks in liquid by about 1 hour. Measurable liquid was observed in orographic clouds 57% of the time.

Plans FY 1987

MESOSCALE SENSOR DEVELOPMENT

The maximum range of the new WPL Doppler lidar will be increased through a careful series of field tests, culminating in a calibration of its backscatter sensitivity against a standard target.

RESEARCH ON MESO-BETA AND -GAMMA SCALES

WPL and the Georgia Institute of Technology will continue their joint study of gravity wave characteristics predicted by a dynamical model, and observed by the six-channel radiometer.

Additional field studies will be conducted, involving research applications of the Doppler lidar to resolve the structure of low-level fronts, upper-level jet streams and associated fronts, mountain waves, downslope wind storms, and the turbulent motions within the planetary boundary layer.

Data from the Meso-Gamma '86 field experiment will be examined to identify all significant events observed. Data sets for selected cases of microbursts, convergence lines, and gust fronts will be compiled for detailed analysis and study.

Modeling studies in support of the SCCCAMP (South Central Coast Cooperative Aerometric Monitoring Program) experiment will continue with flow simulations for different wind directions explored for comparison with measurements from the dual-Doppler radars.

The WPL Doppler radars and IR Doppler lidar will participate in a local field program to investigate microbursts, convective initiation, and the Denver cyclone during the summer of 1987.

R&D ON SYNOPTIC AND MESO-ALPHA SCALES

Although individual ground-based remote sensors are limited by Earth curvature to meso-beta-scale applications, arrays of such sensors can be used to study atmospheric processes up to continental

scale. WPL's planned contribution to this scale is the Profiler, a combined radar-radiometer system for the continuous measurement of profiles of wind, temperature, and humidity. A suitable array of such systems could continuously provide the three-dimensional fields of these parameters on the meso-alpha (200 to 2,000 km) and synoptic (2,000 to 10,000 km) scales for numerical weather prediction (NWP). Such a system would have major value to NWP since the observation data could be (1) time-averaged to remove aliasing of high-frequency components, (2) entered more frequently into the NWP algorithms, and (3) inserted in the form of time derivatives as well as time averages. It is also believed that the wind field data (which are critical to mesoscale NWP) would be considerably more accurate and representative than those available from radiosondes.

Accomplishments FY 1986

SYNOPTIC AND MESOSCALE SENSOR DEVELOPMENT

Considerable progress was made on the Wind Profiler Demonstration Program. A contract was signed with Sperry Corporation to build the UHF Profilers for the demonstration network to be deployed across the central United States. A VAX 11/750 computer was configured and brought into operation as the Hub of the projected network. The access point for data from the Colorado Profiler Network was moved from the WPL S-250 to the Hub computer. The Profiler Technology Transfer Group took over operation of the Colorado Profiler Network of four wind Profilers, made the data available to designated individual users, and completed the link to AFOS (Automation of Field Operations and Services), thus sending Network data out on that national system. The final configuration of the central U.S. network was decided, and the Central Region of NWS began site surveys that will lead to the selection of specific locations. A 15-min videotape on wind Profilers was made and circulated to more than 100 businesses and institutions; four issues of an occasional information bulletin were sent out to 500 individuals in government, universities, and business.

Two significant documents were completed: a high-level description of Profiler data available from the Hub, and the final draft of the NWS Assessment Plan for the Profiler network. A list of pertinent Profiler technical and project documents and publications was submitted to the NWS Technical Library. The development plan for the wind Profiler Demonstration Project was updated. At the end of FY 1986 the wind Profiler Demonstration Program and Profiler Technology Transfer Group were transferred to ESG.

Modifications were made to the 915-MHz radar at Stapleton Airport (Denver) to allow observation and analysis of wind data with high temporal resolution. It was shown that individual wind profiles obtained in about 1 min could depict the details of wind structure during frontal passages. The addition of this high-data-rate mode expands the role of this radar for research into clear air turbulence, data processing methods, and measurement of the variance of radial velocity.

An antenna with five beam-pointing positions was used with a 405-MHz radar at Platteville, Colorado, to determine the precision of wind measurements made by wind Profilers. The precision of hourly-averaged u and v wind components was found to be about 1 m s^{-1} for two- or three-beam Profilers, but two-beam systems have an additional error caused by vertical motion. The rms value of this error was 1.3 m s^{-1} for data obtained in February 1986. Three-beam systems measure the vertical motion and do not have this error; however a bias of about 0.04 m s^{-1} was found in the vertical velocity measurements.

A 90-GHz radiometer was designed and assembled, and is being field-tested for joint use with WPL's existing steerable-beam dual-channel radiometer; theoretical calculations indicate that this additional channel will significantly improve remote soundings of water vapor and cloud liquid.

WPL's 405-MHz wind Profiler was operated as a boundary layer/mesoscale wind Profiler for several months in 1986. Wind profiles were measured with height resolution of 150 m to 4.5 km MSL and with height resolution of 450 m to 7–8 km MSL, using less than 5 W average power. The lowest

altitude for wind measurements was about 200 m above ground. Individual profiles were obtained every 2 min, and averaged profiles were obtained in 20 min.

The linear frequency-modulated ("chirp") pulse waveform was evaluated as a radar waveform for radars that require very short dwell times. This waveform would be useful for airborne radars or ground-based radars with rapid antenna scanning. It is also useful for clear air radars, in which good range resolution is required but observation time can be long.

A study of the colinear-coaxial antenna used with some wind-profiling radars showed that improvement in sidelobe performance could be achieved by proper treatment of the final element in the row of colinear elements. An existing radar is being modified to incorporate these changes.

A comparison of wind fields measured by Doppler lidar and by the ground-based 915-MHz UHF Profiler was completed. Results, based on comparisons of more than 380 data pairs, showed that radial measurements agreed to within an rms difference of less than 1 m s^{-1}.

A study was performed to determine whether operational microwave radars could be used for wind profiling. Although the wavelength of most operational radars is too short to allow routine wind measurements above a few kilometers altitude, these radars can provide some wind information for very little extra cost. Some military radars can contribute limited battlefield wind data, and the NEXRAD weather radars will measure wind profiles in some weather regimes.

RESEARCH ON SYNOPTIC AND MESO-ALPHA SCALES

The relationships between temperature and vertical velocity variance were examined to determine whether wind-profiling radars could be used to measure the height distribution of temperature gradients. Theoretical relationships, verified by in situ instruments on the Boulder Atmospheric Observatory (BAO), indicate the potential for identifying temperature inversions from wind measurements. Significant improvement in temperature profiles measured by microwave radiometers would result if the height and strength of temperature inversions could be obtained from wind Profilers.

A study was made of the diurnal variations of backscattered power from VHF wind Profilers. The diurnal variations are observed during the summer months and are due to enhanced turbulence associated with afternoon convection. The diurnal variations become indistinct during the winter months.

In a collaborative effort between WPL, NCAR, and CIRES, the NCAR/Penn State mesoscale numerical weather prediction model was used to assess the potential impact of the forthcoming National Wind Profiler Network upon mesoscale numerical weather prediction. These simulation experiments were used (1) to demonstrate procedures for recovering detailed frontal and inversion layer temperature structure from vertically smooth radiometric thermodynamic observing systems, given the high time resolution and detailed vertical wind profiles from the simulated Profiler network, and (2) to assess the effect of composite observing systems (wind Profiler plus radiosondes, wind Profiler plus ground- and satellite-based radiometric thermal and moisture retrievals, etc.) on short-range (approximately 12–24 h) mesoscale predictability.

Case studies were carried out using wind Profiler measurements from the five-Profiler WPL Colorado Wind Profiler Network. Diagnostic calculations of vorticity, divergence, and continuity equation vertical velocity revealed the ability of network-configured Profilers to document the hourly evolution of the meso-alpha-scale circulations associated with selected weather events. Results show the expected correlation between periods of heavy snowfall, and meso-alpha ascent within the network. Similarly, cases of strong mountain-lee downslope flow were diagnosed as strongly subsident within the network, in agreement with NWS/NMC forecasts.

Plans FY 1987

SYNOPTIC- AND MESO-ALPHA-SCALE SENSOR DEVELOPMENT

Construction of a transportable boundary layer/mesoscale wind Profiler, started in FY 1986, will be completed. The radar will have a scannable 6-m-diameter antenna and will transmit about 1 kW peak power. The first use for this radar will be to verify the performance of fixed-beam wind Profilers in precipitation. It will also be used in boundary layer and mesoscale experiments.

The calibration of the three dual-channel radiometers of the Colorado Plains Triangle Network will be completed. This calibration is done by means of individual side-by-side tests with the mobile and steerable dual-channel instrument.

The design will be completed and an RFP will be prepared for procurement of a state-of-the-art multichannel radiometric Profiler of temperature and moisture.

The impact of the 90-GHz radiometer in supplementing the existing WPL dual-channel system for vapor and cloud liquid measurements will be investigated experimentally.

Tests will be conducted to determine how much UHF radar measurement of inversion heights improves radiometric temperature retrievals at the Denver WSFO.

A new antenna will be installed on the VHF radar at Platteville. This antenna will incorporate several changes that should result in better sidelobe performance.

Improved data processing algorithms will be developed for wind profiling with UHF radars during precipitation. Present algorithms work well for widespread precipitation but not in intermittent rain and showers.

The 915-MHz radar will be modified to include a 15-m range resolution mode using the chirp pulse waveform.

RESEARCH ON SYNOPTIC AND MESO-ALPHA SCALES

Observations from the Colorado Wind Profiler Network will be used in additional case studies of fronts, jet streams, and synoptic short waves.

Mesoscale numerical predictions of moisture profiles will be tested as a method of improving the vertical structure of the remotely sensed profiles.

The performance of UHF wind Profilers in precipitation will be analyzed. Data from the 915-MHz radar at Stapleton Airport and the new transportable 405-MHz radar will be used for this study.

The existing radiometric Profiler data base will be used to test the applicability of Kalman filtering in improving temperature and moisture profile retrievals.

The analysis of wind Profiler performance from the five-beam data obtained at Platteville, Colorado, with a 405-MHz radar will be completed. The temporal changes in the hourly-averaged wind fields will be studied.

AIR QUALITY

NOAA's weather service mission includes the provision of meteorological information and understanding relevant to air quality. WPL contributes to this program through the application of its remote sensors to the measurement of three-dimensional fields of wind, turbulence, and aerosol in experiments relating to air pollution.

Accomplishments FY 1986

A comprehensive data report on CONDORS (Convective Diffusion Observed by Remote Sensors) was published. The report describes the remote sensors used in the experiments, the observing strate-

gies used to measure diffusion from two tracers released simultaneously at two heights, and results that show good agreement with earlier tank and computer-modeling experiments. The findings do not support the conventional Gaussian diffusion approach used in current operational diffusion models.

From analyses of data collected during the ASCOT (Atmospheric Studies in Complex Terrain) Geysers Experiment, a direct correlation was discovered between the drainage flow structure in the Geysers area of California (as observed by acoustic sounders), and the strength of the Pacific Coast marine inversion (as observed by radiosondes in the San Francisco Bay area). Prior to this study, it had been assumed that no such correlation would exist, because of the intervening topographical features.

The physical mechanism responsible for the formation of wave motions in the pooling area surrounding the Tracy Power Plant in Nevada was identified as arising from seiche-like motions within the confined valley. The studies used data collected from tower-based sonic anemometers and Doppler acoustic sounders deployed during the EPA experiment conducted there in 1984.

Lidar and BAO tower data were analyzed from the Stable Plume Experiment, providing the most accurate measurements thus far of the vertical dispersion of an elevated plume during nighttime conditions. EPA's Complex Terrain Dispersion Model underpredicted these measurements by 35%, showing a need for further refinement.

Processing of lidar plume data from EPA's Full Scale Plume Study at Tracy Power Plant was finished, and the results were formally archived for study by air quality scientists. This culminated WPL's 6-year participation in EPA's Complex Terrain Model Development Project.

New software techniques were developed for automatically removing terrain contamination in Doppler lidar data. The algorithm has been used successfully with data from the ASCOT Brush Creek Experiment to identify and correct errors in wind estimates due to terrain reflection.

A WPL ruby lidar obtained weekly profiles of the stratospheric aerosol during most of the year. The aerosol load has diminished to approximately background level, following the injection of large amounts by the El Chichón volcano in 1982. Only minor amounts of new aerosol were seen to arrive over Colorado as a result of volcanic eruptions during the year.

Plans FY 1987

The last phase of the analyses of ASCOT and EPA complex terrain experiments will be completed with the publication of a series of papers in the open literature.

Optimum locations for remote sensors to study pooling effects in the Roan Creek valley in western Colorado will be determined from analysis of data collected in a pilot experiment conducted at the mouth of Brush Creek Canyon. This will be in preparation for the next major complex terrain experiment being planned by DOE.

A study of the drainage flow structure at the BAO will be conducted. The study will focus on the turbulent structure within the low-level jet associated with drainage flow.

CLIMATE

Accomplishments FY 1986

- Completed documentation of three-dimensional atmospheric and oceanic, acoustic ray-tracing codes, HARPA and HARPO, as two NOAA Special Reports.
- In cooperation with AOML, constructed a simple, time-dependent analytical model of El Niño perturbation of sound speed profiles at 85°W, and suggested how proposed acoustic monitoring systems might work, on the basis of application of our three-dimensional ray-tracing simulations using HARPO for propagation modeling.

- Delivered our three-dimensional ray-tracing code HARPO to Scripps Institution of Oceanography, and ran sample cases successfully on the Scripps CRAY computer.

Plans FY 1987

- Prepare a report on the feasibility of using acoustic techniques for monitoring El Niño.
- Develop methods for using three-dimensional ocean-data fields to produce continuous models for use with HARPO; incorporate Scripps modeling methods.

MARINE OBSERVATION AND PREDICTION

Accomplishments FY 1986

MARINE CYCLOGENESIS

Analysis of the NOAA P–3 measurements during the Arctic Cyclone Expedition, January-February 1984, has provided the first documentation of the mesoscale structure of polar lows, ice-edge boundary layer frontogenesis, and cold air outflows from off the Arctic ice pack. These observations have been compared with mesoscale numerical predictions produced by the Norwegian Meteorological Institute mesoscale model for the same cases; the observations have verified the mesoscale structures simulated with the model. Current numerical simulations made in collaboration with NCAR and CIRES researchers using the NCAR/Penn State mesoscale prediction model are providing new insights into the interaction between baroclinic and mesoscale convective processes in the explosive inten- sification of North Atlantic extratropical cyclones.

Recent analysis of surface contour radar (NASA) data obtained during the NOAA Arctic Cyclone Experiment demonstrates the potential for this 36-GHz beam-limited system to map features in sea ice, using backscattered power for incidence angles from nadir to approximately 30° off-nadir. This same instrument has been used to demonstrate the disparity among existing models of fetch- limited ocean wave growth, and to develop a new model.

An algorithm has been developed for retrieving ice concentration, floe and water roughness, and floe freeboard from laser profilometer data gathered during the Marginal Ice Zone Experiment (MIZEX). This information will be used to determine the roughness parameter of the marginal ice zone, important for wind stress measurements. An ice concentration algorithm has also been developed for the University of Massachusetts step-frequency microwave radiometer, which was also onboard the NOAA P–3 during the 1984 MIZEX. This algorithm has been verified against aircraft photography and synthetic aperture radar images.

Acoustic observations of bubble distributions generated by breaking ocean waves were related to turbulence, Langmuir circulation, and thermal convection.

Plans FY 1987

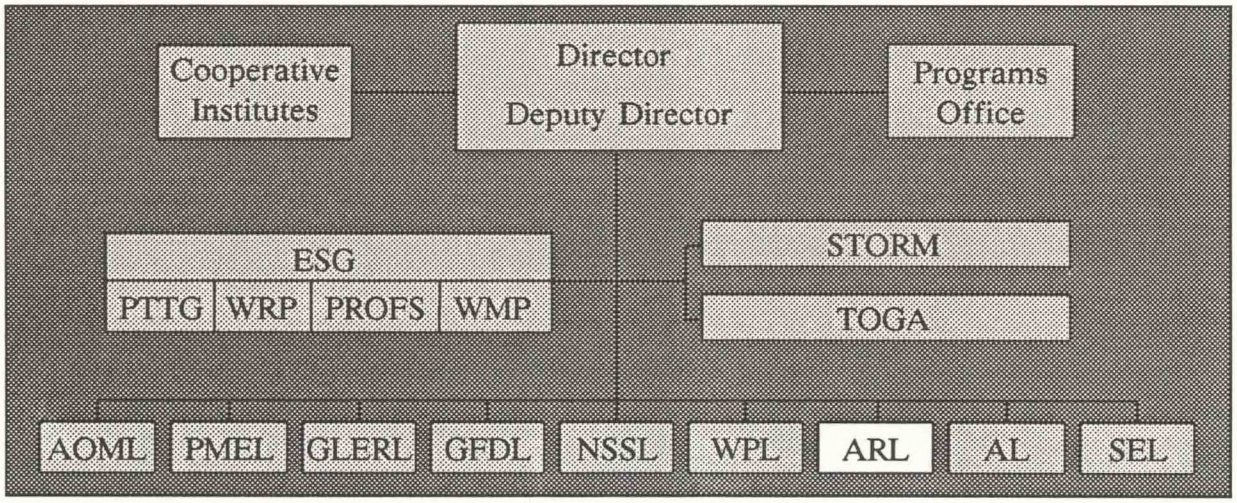
WPL will continue to collaborate with Norwegian, NCAR, and CIRES mesoscale modelers on the numerical simulation of marine extratropical cyclogeneses and mesoscale processes. WPL will participate with PMEL in the February–March 1987 Alaska Storm Program, a NOAA P–3 field program on cyclogenesis, frontogenesis, and coastal orographic flows in the Gulf of Alaska.

A proposal has been submitted requesting $45,000 from the Director's Discretionary Fund of the NASA/Goddard Space Flight Center (GSFC) to initiate the process of upgrading the surface contour

radar (SCR), the GSFC 36-GHz airborne system that produces real-time topographic and backscattered power maps of the surface below the aircraft within a swath equal to half the aircraft alti- tude. The improvements would center on three areas. (1) The scanning antenna assembly would be redesigned to permit ready installation of the SCR on other aircraft. Thus, during the hurricane season the SCR could be put on the NOAA P–3 to measure directional wave spectra. (2) The real-time data processing would be modified to improve the SCR products significantly. (3) The RF section would be evaluated to look for ways of improving signal level.

Using both laboratory data and data from the September 1986 Cordova Channel experiment, WPL will determine the feasibility of measuring profiles of transverse current, refractive turbulence strength, temperature, and salinity in turbulent tidal channels and along paths in the deep ocean.

A report will be prepared on the role of bubbles caused by breaking ocean waves in the entrainment of carbon dioxide bubbles into the water column. Acoustic scattering properties of bubbles will be investigated to determine the feasibility of measuring the bubble size spectrum, with a view to developing acoustic remote sensors of carbon dioxide flux in the ocean.



AIR RESOURCES LABORATORY
Silver Spring, Maryland
Lester Machta, Director

The Air Resources Laboratory (ARL) includes a headquarters group in Silver Spring, Maryland; the Field Research Division in Idaho Falls, Idaho; the Atmospheric Turbulence and Diffusion Division (ATDD) in Oak Ridge, Tennessee; the Meteorology Division in Research Triangle Park, North Carolina; the Sun-Climate Staff, the Air Quality Division, and the Geophysical Monitoring for Climatic Change Division (GMCC) in Boulder, Colorado; and GMCC observatories at Mauna Loa (Hawaii), Barrow (Alaska), the South Pole, and American Samoa. The Climate Research Program was transferred to ARL from the Environmental Sciences Group at the beginning of FY 1987.

ARL research is geared to needs of users, who are frequently other Federal agencies with related missions. Funding and guidance derive from this association through interagency agreements. In some cases the ARL unit under contract to another agency acts as its meteorological arm to provide meteorological guidance. Most ARL research deals with the use of meteorology to understand and predict human influence on the environment, especially with regard to the atmospheric transport and diffusion of toxic effluents including radioactive materials. General areas of study include turbulence and diffusion in the atmosphere, atmospheric trajectories from microscales to global scales, meteorology of air pollution, CO_2 and climate, acid rain, and monitoring of atmospheric constituents for climatic change. Following general descriptions of the work of the ARL groups, ARL research activities are described here under two main headings, Air Quality and Climate. Many of these activities involve cooperation among the Divisions.

HEADQUARTERS GROUP

The research group in Silver Spring develops models that simulate local, regional, and global transport and diffusion of pollutants injected into the atmosphere. Mesoscale and regional-scale versions of these models are being used extensively to evaluate the environmental effects of various types of energy production. Air-sampling programs and other field experiments are conducted to provide data for model verification. Major funding for this work is provided by the Department of Energy (DOE) Office of Health and Environmental Research and other agencies. Research is being carried

out on total-ozone and ozone-profile data and on the sources, transport, and deposition of acid precipitation. Climate studies include research on the sources and sinks of CO_2 in the atmosphere, on global temperature and humidity changes, and on sunshine duration and cloudiness over the contiguous United States.

FIELD RESEARCH DIVISION

Most of the research of ARL's Field Research Division in Idaho is sponsored by the Nuclear Regulatory Commission (NRC), DOE, and the Environmental Protection Agency (EPA). It is directed toward current and anticipated environmental problems associated with the release to the atmosphere of toxic and undesirable effluents by our industrialized society. These problems include the quantification of downwind atmospheric dispersion contributed by the meander of plumes under light wind and inversion conditions, the effect of the land-sea interface, the effect of surface roughness and complex mountainous terrain, measurement of the vertical as well as the horizontal profile of plume concentration, and measurement of air trajectories. Tracer gas techniques and radar-tracked, constant-level balloon trajectories as well as standard meteorological profiles of wind and temperature are used in full-scale field experiments to address these problems and provide the necessary data to verify transport and diffusion models.

ATMOSPHERIC TURBULENCE AND DIFFUSION DIVISION

The Atmospheric Turbulence and Diffusion Division (ATDD) in Oak Ridge is generally concerned with air quality. ATDD conducts research on the physics of the lower atmosphere, with emphasis on the processes contributing to atmospheric transport, dispersion, and deposition, and on the development of models using the results of this research. Research is directed toward practical issues important to both NOAA and DOE's Oak Ridge Operations Office; the largest single source of support is the DOE Pollutant Characterization and Safety Research Division. Additional sources of support include NOAA, EPA, the Department of Defense (DOD), and NRC. The research program is divided into four main areas: plume transport and diffusion in the planetary boundary layer, complex topography, atmosphere-canopy interactions, and dry deposition. A fifth component makes use of wind-tunnel modeling to address questions of near-field dispersion and deposition arising in the four main areas of research. Studies are conducted in close collaboration with Oak Ridge National Laboratory and with atmospheric science units at other national laboratories, universities, and Federal agencies.

METEOROLOGY DIVISION

Meteorology Division support and services to EPA include theoretical and experimental studies of the physical processes affecting transport, diffusion, transformation, and deposition of air pollutants; development, evaluation, modification, and dissemination of air quality simulation models for inert and reactive pollutants; effects of air pollutants on weather and climate; and studies to define the relationships between air quality and meteorological quantities.

The Meteorology Division also provides operational support to various EPA groups. This includes technical advice; applications of air quality simulation models; evaluation of the meteorological portions of state implementation plans, environmental impact statements, and requests for variances; expert testimony at public hearings and judicial proceedings; emergency field services; preparation of technical staff reports and documents.

SUN-CLIMATE STAFF

The Sun-Climate Staff conducts fundamental research on the causes and mechanisms of climatic change, on time scales of months to decades, including solar variability as a possible cause. The application is directed toward, but not limited to, climatic change in the United States. The approach is to

develop understanding of climatic processes through analytical studies using climatic, oceanographic, solar radiation, ozone, and other data, principally those representative of the current century. Research on the temporal variations of solar ultraviolet (UV) radiation, their stratospheric effects, and possible coupling to the troposphere and climate is conducted using measurements from the Solar Backscatter UV (SBUV/2) instruments aboard the NOAA series of satellites and other sources, and using theoretical models of the stratosphere and stratosphere-troposphere coupling.

A ground-based system to measure the secular characteristics of solar spectral changes in UV, visible, and near-infrared wavelengths has been under development since 1980. The effects of atmospheric attenuation on these surface-based measurements are also being studied.

GEOPHYSICAL MONITORING FOR CLIMATIC CHANGE DIVISION

The mission of the GMCC Division is to measure, over a long period of time, atmospheric greenhouse gases and the long-range transport of aerosols in the atmosphere. The measurements, at NOAA's four GMCC baseline observatories and other locations, are made to determine whether these gases and aerosols are changing with time and to identify natural and anthropogenic sources and sinks as well as temporal and hemispheric gradients and global budgets. Greenhouse gases and aerosols interact with solar and terrestrial radiation, and thus changes of these substances can produce climate changes.

Air Quality Group research is directed to (1) improving the understanding of the mechanisms responsible for the formation of acidic aerosols; (2) elucidating the effects of these aerosols and of trace gases on the formation, colloidal stability, optical properties, and chemical composition of clouds; and (3) supplying observational data to validate and improve the acid deposition models currently under development.

CLIMATE RESEARCH PROGRAM

The Climate Research Program, a joint enterprise with the Cooperative Institute for Research in Environmental Sciences (CIRES), was transferred to the Air Resources Laboratory at the beginning of Fiscal Year 1987 (see the Environmental Sciences Group section for Accomplishments and Plans). The Climate Research Program has three broad functions:

- To maintain a global data set describing climate fluctuations since the mid-1800s over oceans and continents.
- To perform interpretive diagnostic studies of climate fluctuations on time scales from weeks to decades.
- To improve climate prediction through the development of real-time indices and evaluation of predictions.

AIR QUALITY

ATMOSPHERIC TRANSPORT

Accomplishments FY 1986

Analysis of CAPTEX (Cross-Appalachian Tracer Experiment) data led to division of the long-range transport model into meteorological and dispersion/transport sections. The meteorological section uses all available surface and rawinsonde observations to generate gridded fields. At the same

time, estimates of vertical mixing are calculated using surface layer theory. The transport/ dispersion model uses these gridded data to estimate pollutant concentrations. The grid is compatible with grids of the National Meteorological Center (NMC), so that the same dispersion code can be run with diagnostic or prognostic data. The essential feature of the model is the specification of the vertical mixing. Analysis of the CAPTEX experimental data has shown the importance of this parameter; the concentrations are not uniform within the mixed layer.

Quality assurance and analysis of the CAPTEX sampling data continue in an effort to make the data compatible for model evaluation. Analyses have shown that, even though the general synoptic situations were similar for all the Dayton releases and similar for the two Sudbury releases, the individual events differed markedly, thus providing a unique challenge to the modelers.

A new field experiment ANATEX (Across North America Tracer Experiment) is being planned. It will include routine tracer releases and air sampling over a wide network as far as 3000 km from the source.

Two new tracers will be used for ANATEX with an existing chromatographic analysis system. They will be released from Glasgow, Montana, and St. Cloud, Minnesota, between 5 January 1987 and 29 March 1987. The chromatographic separation is being improved. Releases will be conducted from both sites every $2\frac{1}{2}$ days, thereby providing 33 alternate day and night releases. Different tracers will be simultaneously released from each site, and ground-level sampling at 75 sites will last for 12 weeks. These sites will be located near all the regular National Weather Service (NWS) upper-air rawinsonde stations in the United States and Canada within 3000 km east of Glasgow between 25° and 55°N and go to 105°W longitude and also along two arcs at about 1000 km and 1600 km from Glasgow. Supplemental upper-air soundings (0600 and 1800 GMT) will be made at the two source sites and four rawinsonde stations during the 12-week period.

Significant dimethyl sulfide (DMS) concentrations were measured within the Planetary Boundary Layer (PBL); near Boston, Massachusetts, in a winter with strong northwest winds, the mean value was 6.2 pptv, but at the lowest altitude near Bermuda in June, the range was 30 to 195 pptv. A steep vertical gradient was observed, indicating PBL removal rates comparable with mixing times. DMS is of interest because it is the primary natural SO_2 precursor over the ocean. Long-lived trace gases, measured at the East Coast and Bermuda, were indicative of long-range transport within the PBL.

A Marine Planetary Boundary Layer (MPBL) chemistry model was developed. Simulations were performed for clean-air conditions and for several polluted-air situations. This photochemical model was found to reproduce accurately the major features that characterize the sulfur cycle in the marine atmosphere. In particular, the model predicted O_3, SO_2, SO_4^{2-}, and NO_3^- levels in good agreement with field observations. The DMS emission rate necessary to reproduce observed marine concentrations was found to be consistent with other estimates.

The Air Quality Group participated in a continuation of the Processing of Emissions by Clouds and Precipitation (PRECP) experiment. Flights were conducted in the vicinity of Syracuse, New York, and Raleigh, North Carolina, during January, and the latter part of February and early March, respectively. A suite of chemistry measurements was made, including SO_2, O_3, NO_2, NO_x, CO, SO_4^{2-}, HNO_3, aerosol size distributions (0.1 to 800 μm diameter), and trace metals.

Trace chemical distributions across cold fronts were mapped on several flights. The data suggest that trace gases with a surface source were being transported into the free troposphere along the sloping boundaries of the cold fronts. Also, using CO as a tracer, we are estimating the rate of transport of boundary layer air into the free troposphere.

Two flights circumnavigated low-pressure systems. These flights were designed to map the distributions of chemical parameters in a winter cyclone at two altitudes. It was found that PBL air from the warm sectors of the cyclones was being transported upward and into the occluded regions of these storms. Then cloud and precipitation processes were scavenging the trace chemicals and depositing them as precipitation in the storms' cold sectors.

The field phase of a research project in the Grand Canyon was carried out by the Air Quality Group in cooperation with the National Park Service during 1984. The purpose of the experiment was to describe the dynamics of air flow in the canyon to enable Park Service personnel to burn understory vegetation without impairing visibility in the Class I area.

The results of this study are now complete. It was found that airflow below the rim level moves predominantly parallel to the canyon during coupled flow conditions (where air from above is interacting with air from below the canyon's rim). These conditions are most often associated with periods of clear days and nights. At other times a strong shear layer was present near the canyon's rim level. Air below this layer appeared to be draining gently downriver. Above this layer, synoptic-scale forces predominated. Winter months appeared more prone to this decoupled (or drainage) behavior. Shear layers present at lower levels within the canyon may have been the product of a slow erosion process from above or the establishment of a radiation inversion. They appeared to act as an alternate bottom to the canyon for airflow purposes.

EMERGENCY OPERATIONS

NOAA/ARL is responsible for issuing official statements on the transport and dispersion of radioactivity following a planned or accidental radioactive release in the atmosphere, as outlined in an Interagency Memorandum of Understanding. During the Chernobyl accident, NOAA's representative on the Presidential Task Force (the ARL Director) was briefed daily with results from operational computer programs developed by ARL specifically for emergency response. The timing and position of the air containing radioactivity entering the United States were well forecast. As a result of the new experience of making calculations during an accidental radioactive release of unknown dimensions, the operational programs are being revised and updated for greater efficacy under a variety of planned and accidental release conditions.

Plans FY 1987

The first field season of the Central U.S. RADM Test and Assessment Intensives (CURTAIN) is being organized. Intensives are being designed to provide observational data to support development of the NCAR Regional Acid Deposition Model (RADM) development. Trace gas and aerosol data will be collected in the central and southern Mississippi River valley both to assess the predictive capability of the RADM and to improve the model itself. Research flights originating in the vicinity of Pine Bluffs, Arkansas, using the NOAA King Air, will begin in January 1987; they will be divided into four 10-day field intensives during the winter, spring, summer, and fall.

The aircraft will be used to measure SO_2, O_3, HNO_3, SO_4^{2-}, trace metals, C1–C5 hydrocarbons, meteorological quantities, and position. These measurements will be used to assess the utility of the RADM model on a case-by-case basis and to establish the background concentrations of the various chemical species for RADM initialization.

A pre-ANATEX background concentration study will begin 1 October 1986 and last for 1 month. Background sample analysis and operation readiness will follow until ANATEX begins in January 1987. ARL will coordinate the entire 3-month field experiment and assure quality of all the measurements.

We will continue transport and dispersion model development and evaluation using measured data from CAPTEX, the Atlantic Coast Unique Regional Tracer Experiment (ACURATE), and the Metropolitan Tracer Experiment (METREX). We will also work with DOE to improve the capabilities for short- and long-range tracer field experiments.

ATMOSPHERIC TRACERS

Accomplishments FY 1986

The Field Research Division continued its participation in the Federal Aviation Administration (FAA) flight test program of the helicopter vortex wake/downwash flowfield by supplying the meteorological profile and turbulence instrumentation in support of the tests. The second phase of the tests was run during May and June 1986.

Extensive measurements of low-altitude winds, temperatures, and balloon trajectories continued for the Argonne National Laboratory (ANL) program for transient reactor tests at Argonne West nuclear reactors. Post-test model calculations of trajectories, diffusion, and exposure from postulated airborne radionuclides were prepared.

Nuclear powerplants are required to have Atmospheric Transport and Diffusion (ATD) models capable of making dose assessments in the event of an emergency. Under an NRC contract, the Field Research Division developed methods of evaluating ATD models. Data cases have been assembled that test a model's performance under a variety of situations. Reference models were selected to compare model results from these test data sets. Evaluations were performed on ATD models used at many United States operating nuclear powerplants. Data are being used to verify models of complex coastal environments.

EPA-sponsored developmental research continued on an advanced operational system for tracking multiple Lagrangian markers (tetroons) on a regional scale. An experimental prototype has been developed of a miniaturized tetroon transmitting and receiving system employing LORAN-C and Omega systems and capable of providing continuous real-time data on longitude/latitude, ambient pressure (altitude), and temperature. Additional field testing was accomplished during FY 1986 to ranges of 1000 miles.

Five gaseous tracer releases and sampling support were provided during the South Central Coast Cooperative Aerometric Monitoring Program (SCCCAMP) field study covering the area from the Los Angeles Basin to Santa Barbara. A central coastal complex terrain diffusion tracer and sampling program was conducted in Santa Barbara and San Luis Obispo Counties. Tetroons, aircraft measurements, and 150 ground samples were used.

Meteorological data were applied to the Idaho National Engineering Laboratory (INEL) site in meeting EPA Prevent Significant Deterioration (PSD) requirements. The data were used to drive EPA-approved models, to assess the effect of INEL facilities on the regional environment.

We completed and sent to NRC an evaluation of nuclear powerplant operators' emergency models. Modeling calculations for daily, weekly, and monthly normalized concentrations at all nuclear operating facilities at INEL have been supplied to DOE since 1981.

Plans FY 1987

A report to NRC will describe the methods and data cases used to evaluate atmospheric transport and diffusion models. Reference models will be compared.

Nuclear powerplant atmospheric transport and diffusion models will be evaluated upon request by NRC.

A prototype gas chromatograph will be developed and tested for the automated gas chromatography laboratory. This prototype will be used to analyze the next-generation types of gaseous tracers suitable for regional and larger scale studies.

The FAA helicopter vortex/wake downwash study will continue through FY 1987.

Prototype samplers will be adapted from existing units for extended-period sampling of next-generation gaseous tracers. Alternate designs will be assessed.

The Field Research Division will carry out a 200-km diffusion study in California's Central Valley from Modesto to Chico and extending into the Sierra Nevada range.

We shall test wingtip vortices of low-flying aircraft, ≤ 600 ft MSL, in support of U.S. Air Force drop tests.

A long-range tetroon study in conjunction with air quality sampling 200 miles off the coast, over San Diego, and north over the West Coast of the United States will be made in conjunction with the National Center for Atmospheric Research (NCAR).

PLUME DISPERSION

Accomplishments FY 1986

Analysis of the data from the recently completed METREX has confirmed model results that suggested that winds would shift 10° to 20° clockwise, owing to the enhanced vertical mixing over an urban area. Dispersion model calculations indicated the importance of having adequate spatial density of meteorological sites because a single site was not sufficient for calculating dispersion. The tracer data also showed the influence of the local terrain. Although the Potomac River valley is at most only 100 m below the surrounding terrain, tracers tended to remain within the river valley. Other results showed that the tracer could persist over the sampling sites for exceptionally long periods. This was attributed to tracer lagging in the lower layers of the atmosphere, where there is less wind and mixing.

A field program to study the intermittency of the nocturnal planetary boundary layer was initiated, with experimental focus on the Walker Branch Watershed research area near Oak Ridge and on the Stone Mountain Observatory near Atlanta (operated by Georgia Institute of Technology). The experimental program is designed to provide data on the frequency of breakdowns of the stable planetary boundary layer. These breakdown events are identified by sudden increase in windspeed, temperature, and ozone concentration at the surface as turbulence mixes upper-level air to the ground surface. At both field locations, windspeed, wind direction, temperature, ozone, and atmospheric thermal structure are measured continuously throughout the night. Initial results indicate that breakdown events occur at both locations, and that they contribute significantly to vertical diffusion processes during stable conditions.

An extensive body of micrometeorological data (derived in an experimental program conducted by the U.S. Air Force from 1964 to 1984 at Edwards Air Force Base, California) has been condensed and is being used to study relations between dispersion coefficients and micrometeorological properties, and to study the uncertainty of air parcel trajectory calculations. The unique set of microscale data is continuous over a region of fairly uniform terrain.

ATDD and a Brazilian power company have undertaken a joint field study to characterize atmospheric transport and diffusion at the coastal site of a Brazilian nuclear powerplant (Angra I). Phase I experiments were designed to address questions of site representativeness with respect to the existing meteorological monitoring system. Experimental teams from ATDD and Brazil completed a 2-week intensive sounding program, coupled with trajectory studies using neutral-lift balloons. As expected, dispersion in the vicinity of the site was found to be dominated by local land/sea breeze effects. Marked changes in the local flow structure were observed during periods when the northern slopes of the surrounding hills were in shadow.

A simulation of the dispersion of heavy gases produced by chemical reactions was developed, by modifying and combining existing models describing atmospheric wind fields, puff dispersion, and chemical reactions. The purpose is to produce a model for assessing site risk.

Plans FY 1987

- Records from field studies in the area of St. Louis, Missouri, will be analyzed for evidence of intermittent breakdown of the nocturnal stratified boundary layer.
- Phase II experiments at the coastal reactor site in Brazil will be conducted in the spring of 1987. Smoke releases will be photographed and analyzed in order to extrapolate puff dispersion parameters appropriate for numerical model formulations.
- The three-component heavy-gas-dispersion model developed by ATDD will be condensed into a single code, suitable for application in the event of an accidental release to the atmosphere.

DISPERSION IN COMPLEX TERRAIN

Accomplishments FY 1986

ATDD now has responsibility for planning and organizing large, multilaboratory field experiments for the DOE Atmospheric Studies in Complex Terrain (ASCOT) program. Initial plans for the next major field study were drafted during FY 1986, and exploratory investigations were conducted at a field site in northern Colorado.

Two complex terrain modeling activities are well under way at ATDD, as part of the ASCOT program. A highly parameterized "hydraulic" model of valley drainage flow was tested and found to give qualitatively reasonable results, in comparison with the ASCOT Brush Creek (Colorado) data set. The model has been modified to account for the effects of sidewall flows; as now simulated, these flows account for about 50% of the predicted volume discharge from the valley.

An additional ATDD/ASCOT modeling effort began recently, to modify a newly developed puff dispersion model, using tracer data obtained in the 1984 ASCOT field program as guidance. It is anticipated that this model, after completion of the present work to include complex terrain flow and turbulence effects, will be a good candidate for general calculations of complex terrain dispersion.

Plans FY 1987

- The next major ASCOT field experiment will probably be conducted in autumn 1988. A preliminary study involving at least 7 DOE laboratories and 40 or more people will be carried out late in 1987, to determine optimum instrument locations, especially for remote-sensing systems. The main experiment in 1988 and its forerunner in 1987 will extend the scope of the study to a significantly larger region than has previously been included, covering the merger and possible pooling of cold air drainages from several valleys near the Colorado River.
- The parameterized hydraulic model of drainage flow will be tested using data from more complex sites and more computationally intensive models. Dispersion routines will be added to model tracer dispersion in valleys. Initial modifications made to the puff dispersion model for complex terrain will be tested against the 1984 ASCOT tracer data set.

AIR QUALITY DISPERSION MODELING

Accomplishments FY 1986

The preliminary version of the Complex Terrain Dispersion Model (CTDM) was completed on schedule. This model predicts ground-level concentrations under stable- and neutral-case plume im-

pact in mountainous areas. It uses the dividing streamline concept and modifications to potential flow, to predict the transport and diffusion of elevated releases. Several months after the CTDM was released, a workshop of invited experts was held to review the model and make recommendations on further developments. The workshop results supported the scientific basis of the model, but suggested changes that would make the model more useful.

Major updates to an integrated puff model (INPUFF 2.0) include incorporation of a deposition algorithm and the ability to assess the impact from multiple sources. A preliminary evaluation of INPUFF with an SF_6 data base was published. The results showed a slight tendency to overestimate peak concentrations and a slight bias toward underprediction of peak dosage.

A model estimates dispersion directly from fluctuation statistics at plume level and calculates plume rise and partial penetration of the plume into stable layers, using vertical profiles of wind and temperature. The model user is thus required to furnish meteorological information for several heights above ground. By parameterizing the crosswind spreading and assuming that the horizontal diffusion is Gaussian, concentrations for non-Gaussian vertical plume behavior within the convective boundary layer can be estimated. These techniques have been incorporated in the model. The hourly concentration output files from the model are input to the post-processor for longer averages and maxima over the period of computation.

We carried out research specifically addressing the uncertainty in estimating the maximum concentrations from elevated buoyant sources during unstable atmospheric conditions. A numerical uncertainty analysis was performed using the Monte Carlo technique to propagate the uncertainties associated with the model input. Uncertainties were assumed to exist in four model input parameters: (1) wind speed, (2) standard deviation of lateral wind direction fluctuations, (3) standard deviation of vertical wind direction fluctuations, and (4) plume rise. For each simulation, results characterized the uncertainty in four features of the ground-level concentration pattern predicted by the model: the magnitude of the maximum concentration, the distance to the maximum concentration, and the areas enclosed within the isopleths of 50% and 25% of the error-free estimate of the maximum concentration. It was concluded that the error bounds for the estimated maximum concentration and the distance to the maximum can be double that of the error bounds for individual model input parameters; the model output error bounds for the areas enclosed within isopleth values can be triple the error bounds of the input. These results allow estimation of minimum bounds on errors in model output when reasonable input error bounds are considered.

The first-generation Regional Oxidant Model (ROM1) was evaluated for O_3 predictions for a 2-day episode (3–4 August 1979) in the northeastern United States, and documented. Maximum daily O_3 concentrations for 150 monitoring sites were underpredicted an average of 8%. Maximum concentrations observed in urban plumes were between 22% underprediction and 38% overprediction.

ROM1 was applied in two control strategy applications. The first 9-day simulation, 23–31 July 1980, studied the effect of an urban control strategy on rural ozone concentrations. The second 6-day simulation, 23–28 July 1980, evaluated the effects of reducing hydrocarbon emissions from the Treatment, Storage, and Disposal Facility.

The second-generation ROM processors were modified to account for layer thicknesses varying in time and space and divergent winds. The Carbon Bond Model IV (CBM–IV) chemistry has replaced the Demerjian-Schere mechanism. Hypothetical cases that test each new feature of the model have been implemented.

A user's guide describing the theoretical and computational aspects of the REgional Lagrangian Model of Air Pollution (RELMAP) was published. The guide contains an evaluation of the model, which reveals that seasonal and annual simulations for wet deposition are generally within a factor of 2 of the observed data.

The RELMAP model has been modified to accept a curvilinear coordinate system with user-defined dimensions. The model now accepts particulate emissions and predicts the concentration and

deposition of particulates in two particle-size ranges. The model may be operated to calculate a source-receptor transfer matrix, and its application flexibility has been extended yet again.

A study of the status and needs of research on diffusion in the atmospheric boundary layer indicated that the most important knowledge gap is the lack of an adequate specification of the relevant meteorology. A second major inadequacy is the lack of experimental measurements of plume characteristics up to 100 km from the release point.

Plans FY 1987

Direct meteorological research support to EPA will continue with the development and evaluation of air quality dispersion models for inert and reactive pollutants and the associated meteorological models on all temporal and spatial scales. An important area of continued concern will be the problems associated with model uncertainty and model evaluation procedures. Emphasis in FY 1987 will be on completion of the evaluation of CTDM; examination of the problems related to the dispersion of toxic substances, including conduct of a workshop on accidental toxic releases; and continued evaluation and improvement of ROM and RELMAP.

FLUID MODELING

Accomplishments FY 1986

A cooperative project was completed with the Los Alamos National Laboratory to examine the conditions under which flushing of a valley between two ridges will occur, i.e., to determine when a stable crosswind will sweep the valley clean and when a nearly stagnant region in the valley beneath will form. In this series of towing-tank studies, three experimental parameters were varied: the steepness of the ridge/valley slopes (40°, 27°, and 13°), the separation distance between the ridges, and the Froude number that characterizes the stability of the crosswind. In broad terms, the characteristics of the flow between the ridges may be explained using criteria for boundary-layer separation from the lee side of a single ridge. The downstream ridge appears to induce separation from the lee side of the upstream ridge only when it is steep-sided.

An additional set of streamline trajectories over an axisymmetric hill was measured in the stratified towing tank to supplement the set collected in FY 1985. A stereographic analysis of photographs of dye streak lines from centerline and offset source positions was used to obtain three-dimensional coordinates of streamlines over the hill. This new set of experiments was performed for intermediate stabilities (Froude numbers of 1.0 to 8.0) with the objective of determining the minimum Froude number for which the streamline patterns are essentially the same as those of neutral flow.

Terrain amplification factors were measured for a large matrix of source positions (locations and heights) both upstream and downstream from each of two idealized hills, an axisymmetric hill and a two-dimensional ridge. The results showed that "windows" of 40% excess concentration extend to 1.8 hill heights (h) in the vertical, 14h upstream, and 10h downstream for the three-dimensional hill; and 2.2h in the vertical, 8h upstream, and 15h downstream for the two-dimensional ridge. Maximum terrain amplification factors were found on the downstream sides of the hills, with values of 6.8 and 5.6 for the 2–D and 3–D hills, respectively.

The flow fields around moderately steep hills of triangular cross section and varying crosswind aspect ratio were examined using models immersed in a simulated neutral atmospheric boundary layer in the wind tunnel. Concentration patterns resulting from sources placed upwind of each hill showed strong plume deformations, and terrain amplification factors generally increased with decreasing aspect ratio.

In a cooperative project with the Los Alamos National Laboratory, detailed measurements of flow characteristics downstream of a turbulence-generating grid were used as a basis for calculating particle

diffusion. Results of the calculations were compared with total diffusion measured by a hydrocarbon tracer technique and with relative diffusion determined from analysis of near-instantaneous photographs of smoke plumes. Comparisons between a one-particle diffusion model and the present two-particle model showed that the two-particle model provided a more accurate description of plume meandering and relative diffusion.

An extensive series of comparisons was made between predictions of the Complex Terrain Dispersion Model (CTDM — developed under contract to EPA) and data collected at the Fluid Modeling Facility on flow and diffusion over two- and three-dimensional hills in both neutral and stratified flow conditions. The results showed several shortcomings of the model and suggested several ways in which the model could be improved. These improvements were carried out particularly for neutral conditions.

A detailed series of wind tunnel measurements was made of plume shapes in flat terrain over a three-dimensional hill. These data were analyzed to provide desired information on horizontal and vertical plume deflections and deformations over the hill as well as to provide information on the effectiveness of a "hill surface boundary layer" in mixing of material from an elevated plume onto the hill surface. Detailed results were delivered to the contractor developing the CTDM.

Under a Cooperative Agreement with the Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, the mixing efficiency of grid-generated turbulence was measured in a series of experiments in the stably stratified towing tank. The "mixing efficiency" refers to the fraction of available turbulent kinetic energy that is converted to potential energy, and has important consequences with regard to plume growth in a stratified atmosphere. The results suggest that the mixing efficiency increases monotonically with increasing stability; there is some indication that it approaches a constant as the flow becomes strongly stable.

Under a cooperative arrangement with the Georgia Institute of Technology and EPA/Corvallis, Oregon, a series of stratified towing-tank studies was conducted using models of submerged multiport diffusers emitting buoyant effluent to study mixing of wastewater into a density stratified current. The purpose was to improve the basic understanding of initial dilution performance of ocean sewage outfalls.

A new method to analyze flow visualization studies using digitization of video films was developed and tested. This technique is being used to develop spectra and co-spectra of turbulence in the wake of buildings. This information will be input into more physically realistic models of wake flow than are now available.

Plans FY 1987

Work will continue in the Fluid Modeling Facility, using the wind tunnels and water channel/towing tank to study flow in complex terrain, flow around buildings and other obstacles, and the basic characteristics of flow in the boundary layer.

ACID DEPOSITION

Accomplishments FY 1986

During January 1986, ARL participated in the Western Atlantic Ocean Experiment (WATOX). The objective was to improve estimates of the eastward flux of air pollutants emitted by North America. Instruments for measuring atmospheric gas and aerosol concentrations were provided by scientists from several Government agencies, universities, and research institutions and installed in both the NOAA P–3 aircraft and the NOAA King Air aircraft. Ozone, nitric acid, dimethyl sulfide (DMS), H_2O_2, SO_2, NO_x, CO, NO_2, and PAN were analyzed. In addition, condensation nuclei were meas-

ured, and aerosol scattering extinction coefficients were calculated from nephelometer measurements. A complete set of meteorological measurements was recorded every 10 s for each flight. Dropsondes were used to augment the meteorological data base (see also Atmospheric Transport).

The P-3 flights were conducted over the Atlantic Ocean approximately 200 km from the coast for an area extending from the Florida-Georgia border to southern Labrador. King Air flights were conducted in the vicinity of Boston. Preliminary results tend to confirm that about 30% of the anthropogenic sulfur is transported off North America but nitrogen transport was less clear.

Research in precipitation chemistry made notable progress:

- Aerosols and gases were measured along the Atlantic Coast between Newfoundland and Florida during a major WATOX field experiment.
- The Global Trends Network showed that background amounts of acid-forming materials are about 10% of amounts found in more populated areas such as the U.S. Northeast.
- The measurements of organic acids (formic and acetic) in the atmosphere were vastly improved.
- The sampling protocols for the NOAA GMCC sites were evaluated, and steps were taken to update and revise sampling and analysis protocols.
- Routine operation of 15 National Trends Network precipitation chemistry stations continued. Data for 2 years from two pairs of colocated stations in Texas and Maine have now been collected.
- A second precipitation network intercomparison study was undertaken with the Canadian government in an effort to improve our understanding of trends in North American precipitation chemistry.

Plans FY 1987

In cooperation with the National Trends Network/National Atmospheric Deposition Program, a new precipitation chemistry station will begin operation near an existing station in Meridian, Mississippi. The purpose is to test for differences in precipitation chemistry between the new site, which will be set up according to current protocol, and an existing site, which violates several important siting criteria.

The sampling protocol for precipitation collection at the four GMCC sites was revised to take advantage of recent advances in precipitation monitoring. FY 1987 will be the first year in which all major cations and anions will be measured for event samples from Hawaii and Samoa, event samples and surface snow samples from Barrow, and surface snow samples from the South Pole.

Fluxes of materials measured during WATOX 1985 and WATOX 1986 field experiments will be calculated during 1987. These calculations should provide reasonable estimates of natural and anthropogenic emissions off the Atlantic coast during post-frontal periods with northwesterly flow.

DRY DEPOSITION

Accomplishments FY 1986

The network of "satellite" stations set up to develop and evaluate methods for quantifying dry deposition of selected pollutants at routine monitoring stations is now in the process of expanding to 13

sites. Existing stations are at Oak Ridge, Tennessee; Panola, Georgia; Bondville and Argonne, Illinois; Borden, Ontario; Whiteface Mountain and West Point, New York; State College, Pennsylvania; Pawnee, Colorado; and Sequoia, California. Instrumentation is soon to be installed at Shenandoah, Virginia; Raleigh, North Carolina; and Howland, Maine. Also, equipment has been prepared for extended loan to the Institute of Terrestrial Ecology, Edinburgh, Scotland.

Efforts to expand the subnetwork of "CORE" stations, at which more direct measurements of dry deposition are made to "benchmark" the results derived at other locations, have continued with some small success. In collaboration with EPA, work is in progress to identify a suitable location for a western CORE site, where the research emphasis will be on the role of water stress in controlling dry deposition of sulfur dioxide, ozone, and other trace gases.

The procedure developed to derive dry deposition from routine observations of air chemistry and related surface and atmospheric properties has been tested against special field observations conducted at the Oak Ridge CORE site, and is now being tested using other data sets. This model is now supported by a hierarchy of more complicated simulations of the atmosphere/surface exchange process, which are being improved in parallel with the ongoing experimental effort.

The first results of the satellite network measurement program on dry deposition were prepared for publication. These results indicate that dry deposition of sulfur is approximately equal to wet deposition, on the average in the eastern United States. In accordance with expectations, the ratio of dry to wet deposition varies widely, both with time and with location.

Plans FY 1987

- A description of protocols for routinely monitoring variables for quantifying dry deposition will be published. Data obtained in the expanded satellite network will be analyzed and prepared for publication. Direct comparisons between dry and wet deposition rates of sulfur will be published.

- Nitrogen-species dry deposition data will be reduced and presented.

- Depending on support from EPA, a western CORE site will be established, and work on extending dry deposition analytical routines to arid environments will commence.

ACID RAIN MODELING

Accomplishments FY 1986

Preliminary evaluation studies of the NCAR Regional Acid Deposition Model (RADM) and chemical and meteorological components show that the model has achieved initial success. The first test of RADM's ability to analyze "what if" studies with hypothetical reductions in sulfur emissions was demonstrated in a report.

A design plan for a comprehensive field study to evaluate regional acid deposition models was developed through a series of workshops sponsored by EPA, Electric Power Research Institute (EPRI), and the Canadian government. The plan includes a scientific basis for a primary 35-station surface network and a 30-station concentration variability network. Current effort is directed to planning for aircraft sampling and special chemical surface sites. A request for proposals to implement the plan is pending.

The mesoscale acid deposition model, MesoSTEM, was delivered and will be used to simulate three of the 1984–1985 Philadelphia Mesoscale Acid Deposition Field Studies. Design plans for the

Washington, D.C., Mesoscale Acid Deposition Field Study have been completed. Surface and aircraft sampling will be conducted within 100 km centered on the Washington Monument during the first half of FY 1987. Selected events will be simulated using MesoSTEM.

The final report on the International Sulfur Deposition Model Evaluation (ISDME) is in the review process. It presents an assessment of seasonal and overall performance of eleven statistical and deterministic models in replicating the 1980 spatial pattern of sulfur wet deposition across eastern North America. This assessment represents the first extensive evaluation and intercomparison of these models and provides a benchmark for regional model performance as well as a foundation for future regional model evaluation studies.

Plans FY 1987

During FY 1987, field programs will be conducted around Washington, D.C., to provide event data bases for the evaluation and improvement of MesoSTEM. Major emphasis will continue on preparations for a comprehensive field study to evaluate RADMs.

ATMOSPHERE-CANOPY INTERACTION (FOREST METEOROLOGY)

Accomplishments FY 1986

A pilot study was conducted to measure eddy fluxes of $C0_2$, water vapor, sensible heat, and momentum at the floor of a deciduous forest. A fast-response open-path CO_2 sensor, a three-dimensional sonic anemometer, water vapor sensors, and temperature sensors were used. Midday values of CO_2 efflux from the forest floor typically ranged between 0.30 and 0.45 mg m^{-2} s^{-1}. CO_2 fluxes were correlated with air temperature. A suppression of CO_2 efflux was observed late in the afternoon, and a burst in CO_2 efflux was observed near dusk, independent of temperature. The CO_2 efflux was insensitive to changes in wind speed under the conditions studied. Such measurements could provide new ways to investigate how surface characteristics (especially vegetation) can be included in numerical models. They could also provide basic information on soil atmosphere exchange of trace gases in the natural environment.

In April 1986, a team of ATDD researchers participated in a cooperative experiment conducted in an almond orchard near Chico, California, by the U.S. Forest Service and U.S. Army Atmospheric Science Laboratory. This experiment provided an opportunity to study within-canopy wind flow in an "ideal forest" on level terrain. Wind velocity components were measured above and within the canopy, to yield both mean flow and turbulence information. The results support the contention that turbulent exchange is driven by large intermittent eddies, rather than a uniform, Gaussian distribution of turbulent fluctuations.

A series of multispectral radiative exchange measurements was made at the Walker Branch Watershed forest field site during June 1986. In addition to the ATDD, collaborators included the private sector, the U.S. Army Engineers Waterways Experiment Station, and the NASA Goddard Space Flight Center. The primary objective was to improve canopy thermal radiation exchange models now being developed. Other uses of the information obtained include (1) studies of the spatial and temporal variation in radiative exchanges of a fully-leafed deciduous forest canopy; (2) development of methods for assessing forest ecosystem thermal energy exchange from satellites, airborne, and ground-based measurements; (3) determination of the spectral reflectance distribution of the canopy; (4) evaluation of satellite and airborne infrared methods for detecting objects within a forest canopy; and (5) evaluation of methods for providing "ground truth" for satellite imaging techniques.

Plans FY 1987

- Subcanopy turbulent exchange will be studied in a deciduous forest, with immediate focus on wind and temperature and with subsequent extension to water vapor and other trace gases.
- The role of intermittent flushing of subcanopy air will be investigated, as a mechanism for controlling atmosphere/surface exchange in areas of complex terrain with tall vegetation.

OZONE

Accomplishments FY 1986

The GMCC Division continued to provide the National Environmental Satellite, Data, and Information Service (NESDIS) with total-ozone, ozonesonde, and Umkehr data for validation of SBUV–2 ozone data obtained aboard the NOAA–F satellite.

Total-ozone observations with Dobson spectrophotometers were made during FY 1986 at Bismarck, North Dakota; Caribou, Maine; American Samoa; Tallahassee, Florida; Boulder, Colorado; Poker Flat, Alaska; Mauna Loa, Hawaii; Perth, Australia; and Haute Provence, France.

In a continuing program to upgrade Dobson instruments in the global total-ozone station network, the GMCC Dobson Spectrophotometer Central Laboratory calibrated U.S. instruments 38, 72, and 82; Peru instrument 87; and U.K. instrument 41. Additionally, an International Comparison of Dobson Spectrophotometers was convened by GMCC in Arosa, Switzerland, in August 1986. Thirteen countries with Dobson spectrophotometers as well as three countries with Brewer ozone spectrometers participated. During the comparisons, the majority of the instruments yielded observational ozone data that agreed with GMCC's Dobson instrument 83 values to within 2%.

A new round of spectrophotometer calibrations in the global total-ozone station network was undertaken by means of traveling standard lamps. Results from all stations are expected in 1987. A similar program was conducted during 1981–1983.

Weekly soundings with balloon-borne electrochemical concentration cell (ECC) ozonesondes were conducted at Boulder, Colorado; Hilo, Hawaii; and Edmonton, Canada (in a cooperative program with the Canadian Atmospheric Environment Service). In February 1986, weekly ozonesonde flights were initiated at Barrow, Alaska, and at American Samoa in April 1986. Biweekly ozone soundings began at South Pole in January 1986. During August through November 1986, the frequency of soundings at South Pole was increased to two per week, with funding from NASA.

Umkehr observations were made at six stations: Boulder, Mauna Loa Observatory, Haute Provence, Poker Flat, Perth, and Huancayo.

Analysis of South Pole total-ozone data obtained since 1964 indicated that year-average total ozone has decreased at South Pole by 25%. Largest ozone decreases have occurred during October and November months, but are evident also in other months except February. Additional analyses showed that there has occurred a significant delay, over the years, in the time of stratospheric warming in Antarctica, and, hence, a delay in the time of transport of stratospheric ozone to Antarctica each spring. In 1985, for example, stratospheric warming at South Pole occurred about 3 weeks later than it did in 1964. Although ClO_x and NO_x no doubt destroy some ozone, the change in ozone transport to Antarctica by atmospheric circulation processes may be an important mechanism responsible for the observed ozone decrease.

The ozonesonde and surface measurements at the GMCC observatories permit an assessment of the representativeness of surface ozone observations in describing ozone in the lower troposphere. Surface ozone amounts observed at Mauna Loa during the past 2 years have been closer to normal

than the 1983 values. This has resulted in a decrease in the large positive ozone trend noted earlier. The trend is still, however, highly significant for 1974–1985.

Total-ozone and ozone-profile data for the world were updated through the autumn of 1985. Global total ozone decreased by about 1% between 1984 and 1985, attaining a value nearly as low as in 1983 when the second lowest value of record (since 1958) was observed. This decrease reflects in part the effect of the quasi-biennial oscillation and possibly the transition toward sunspot minimum. The total-ozone decrease between 1984 and 1985 was especially large in Asia, exceeding 6%. Total ozone continued to decrease during the Antarctic spring, and it was found that this depletion has been accompanied by significant cooling of the Antarctic stratosphere. During the last decade, there has been a greater ozone decrease in spring than in other seasons in most climatic zones.

Almost all ozone-profile measurements are made in the north temperate zone. In the 24–32 km layer of this zone the ozone values obtained from ozonesondes were lower in 1985 than in any year since the beginning of the record in 1967, and in the 16–24 km layer the ozone values obtained from Umkehr measurements were lower in 1985 than in any year since the beginning of the record in 1961. In the 32–48 km layer, where anthropogenic influences should be most obvious, the Umkehr-derived ozone values were lower in 1985 than in any previous year since 1961 with the exception of the years following Agung (1963) and El Chichón (1982) volcanic eruptions. However, the continuing presence of volcanic dust from El Chichón makes even the 1985 values suspect. There is little evidence of an increase in tropospheric ozone between 1984 and 1985.

Atmosphere/surface exchange rates of ozone and of related nitrogen species have been measured by ATDD personnel in several field experiments, over both forests and crops. Sensor deficiencies have been identified as sources of considerable uncertainty in such investigations. Development of new sensors capable of operation above and within forest canopies has now been completed. Fast-response O_3 and NO_2 detectors suitable for eddy correlation application were recently produced as a product of this work, but remain to be thoroughly tested.

Plans FY 1987

Electrochemical concentration cell (ECC) ozonesonde data obtained at South Pole in FY 1986 will be compared with 1969–1971 South Pole data, to study the role of atmospheric circulation and ozone transport changes in formation of the Antarctica ozone "hole." To obtain more ozonesonde data for future Antarctica ozone depletion studies, a program of weekly ECC ozonesonde soundings is planned for McMurdo, Antarctica, for 1987.

ECC ozonesonde soundings will continue during FY 1987 at Boulder, Hilo, Edmonton, and South Pole. After a year's operation, ozone vertical distribution measurements with ECC sondes will terminate at Point Barrow and Samoa because of funding restrictions.

A program of ozone observations with balloon-borne ECC ozonesondes began in July 1986 at Lauder, New Zealand, in cooperation with the New Zealand Department of Scientific and Industrial Research. These observations, undertaken in a study of ozone transport to Antarctica, are expected to continue through 1987.

Delays have been experienced in calibration of Dobson spectrophotometers in Sapporo, Japan, and Varanasi, India; and in installation of an automated Dobson ozone spectrophotometer for Umkehr observations at Lauder, New Zealand. We expect to complete these projects in 1987.

Surface ozone measurements will continue at the four GMCC observatories. Results will be compared with ozone vertical profile measurements toward the goal of developing a tropospheric ozone climatology.

An examination of the interaction between rapid chemical reactions and turbulent exchange will be completed.

The total-ozone data and ozone-profile data will continue to be updated as an aid in judging whether the relatively low ozone values in recent years reflect anthropogenic influences on stratospheric photochemistry.

Field tests will be conducted of the newly developed O_3 and NO_2 sensors for eddy correlation. These tests will include extensive intercomparison of instruments.

CLIMATE

SUN- AND MOON-CLIMATE RELATIONSHIPS

Accomplishments FY 1986

The University of Arizona, under an ARL grant, has developed and is testing a solar spectrometer at Mauna Loa Observatory. A permanent building is being constructed to house the instrument, which is designed to measure variations in the "solar constant" from the Earth's surface after adjustment for intervening atmospheric effects.

Analysis of total solar irradiance (S) measurements from the Solar Maximum Mission satellite and from the Earth Radiation Budget experiment on the Nimbus-7 satellite showed that the temporal variations of S result from a competition between facula brightening and the sunspot darkening. All measures of solar activity show strong periodicity (~28 days) caused by the solar rotation of active regions, except in the case of S. The 28-day periodicity is present in both the sunspot darkening and the facula brightening functions, but their opposing effects cause the 28-day line to be missing in S. The temporal variations of the solar ultraviolet (UV) flux measurements from the Nimbus-7 satellite were used to estimate the temporal variations of faculae. A typical pattern for an episode of major solar activity is that the sunspot darkening dominates and a dip in S occurs during the first solar rotation of the group of active regions. During the second rotation, sunspot darkening may slightly dominate. During later rotations, the facula brightenings dominate. Long-term variations appear to be dominated by facula brightening rather than sunspot darkening. The decline of solar cycle 21 was accompanied by small decreases in both S and the facula brightening.

The temporal characteristics of solar extreme ultraviolet (EUV) radiation measured by the Atmosphere Explorer satellite (AE–E) have been compared with those of solar UV measurements from the Nimbus-7 satellite. The temporal characteristics of both the satellite UV data and ground-based measurements of a chromospheric He-I absorption line were shown to agree with those of chromospheric EUV measurements and to disagree with some of the temporal characteristics of the coronal 10.7 solar radio flux (F10). Recommended revisions of the AE–E EUV observations, based on comparison with F10, were shown to be faulty, because the assumption that chromospheric EUV fluxes should vary like the coronal F10 is erroneous. There are systematic differences in the temporal characteristics between coronal radiations and chromospheric fluxes.

Analysis of the short-term variations of the solar UV spectral irradiance in the 160–400 nm wavelength range was completed for 6 years of Nimbus-7 observations. The results indicate that observations at a few key wavelengths may be sufficient to estimate the short-term temporal variations at all UV wavelengths important to the stratosphere. Analysis of the long-term UV variations are now in progress. Some discrepancies have been identified between the long-term trends in the solar UV measurements from the Solar Mesosphere Explorer (SME) satellite and those from the Nimbus-7 satellite. Analyses of the first year of solar UV flux measurements from the NOAA–9 satellite are under way. The NOAA–9 measurements of solar UV flux during the coming rise of the next solar cycle may help resolve the current controversy over the long-term solar UV variations.

An analysis of temperature variation over the contiguous United States at three lunar monthly periods was initiated. Preliminary results indicate that significant temperature variation occurs at the lunar synodic period, and that the amplitude and phase of the relationship varies across the United States. The statistical association appears to be significant, in some regions, during all seasons of the year.

An analysis of precipitation over the contiguous United States was completed. It showed extended periods of below-normal precipitation during the 1930s, 1950s, and 1970s in broad regions of the western and central United States, and during the 1940s, and 1960s in more limited regions of the eastern United States. The recurrence times for reduced precipitation averaged 11.5 and 23 years; the duration of these relatively dry periods averaged 6 years. On the basis of recurrence times alone, extended periods of below-normal precipitation would be expected to begin in the eastern United States in 1986 or 1987, and more broadly in the central and western United States in 1995.

Tree-ring data for portions of the eastern and western United States were obtained from the Tree-Ring Laboratory of the University of Arizona. These data were used to calculate a drought area index. Preliminary analyses of these indices show relatively little coherence between the eastern and western United States. In the West the principal variability in drought area index is at approximately 65–85, 23, 19, 5.8, 4.1, and 2.3 years. In the East the principal variability is at approximately 7.5–8.0 years. There is significant, but less, variability at 3.8 and 3.3 years. Thus, the principal variation in drought area index for the eastern United States may be a result of the interaction of a forcing variable at (half) the quasi-biennial period (~ 1.15 years) and the annual period.

Plans FY 1987

Guidance will be obtained from the peer community, and recommendations will be developed concerning the operation of the (Univ. of Arizona) solar spectrometer at Mauna Loa Observatory.

Analyses of the intermediate- and long-term variations of 6 years of Nimbus-7 observations of the solar UV spectral irradiance and their relation to the short-term results will be completed and published. Primary emphasis will be on determining whether the long-term variations can be well explained by observations at a few key wavelengths. Analyses of the first year of solar UV measurements from the NOAA–9 satellite will be completed and published.

Analysis of precipitation data and tree-ring data for the contiguous United States will continue in an effort to identify possible causes of drought. Principal effort will center on (1) 11.5-, 19-, and 23-year variability in the western and central United States, possibly related to solar variability and lunar position; and (2) 7.5–8.0 year variability in the eastern United States, possibly related to the stratospheric quasi-biennial oscillation. The goal is to provide a technical basis for anticipating drought in the United States, indicated from recurrence alone and possibly beginning in the central and western United States during the mid-1990s.

DIAGNOSTIC CLIMATE STUDIES

Accomplishments FY 1986

About 100 years of SST data in the eastern equatorial Pacific, the Southern Oscillation (SO), Indian monsoon rainfall, and some hemispheric temperature records compiled by British scientists were examined for interconnections in their interannual changes. There is a well-documented relationship between the SO and SST in the El Niño regions. Changes in the SO and SST tend to anticipate changes in hemispheric temperatures except for Northern Hemisphere continental temperatures. The Indian monsoon rainfall tends to anticipate the SO and the SST in the El Niño region. It also appears to be negatively correlated with Southern Hemisphere continental temperatures in the succeeding

Southern Hemisphere summer. There were suggestions that these relationships change over long time periods; the period from roughly 1920 to 1950 seems to have been one in which almost all relations were weaker than at the other times. Also, strong relations between antecedent pressure changes and the monsoon rainfall found since World War II do not seem to have been present prior to the war.

Global tropospheric and low-stratospheric temperatures obtained from a 63-station radiosonde network have been updated through the summer of 1986. The tropospheric cooling in evidence since 1983 ceased in the summer of 1985, and has been followed by appreciable warming, in accord with the changes in sea-surface temperature in the eastern equatorial Pacific. In the low stratosphere, global temperatures were lower in 1985 than in any year since the beginning of the record in 1958, owing largely to very low temperatures indicated for the tropics and Southern Hemisphere. However, in the low stratosphere of the north polar zone the temperatures were anomalously high in early 1985. There has been a pronounced springtime cooling of the Antarctic low-stratosphere in the last decade, possibly associated with a pronounced decrease in springtime total ozone during this time. During the last 25 years, tropospheric temperatures have cooled in that season relative to the other seasons in both hemispheres.

Beginning with the winter of 1984–85, and continuing through the summer of 1986, relative humidity, mixing ratio, and precipitable water have been obtained on a routine basis from the 63-station radiosonde network used in the study of global temperature variations. Between early 1985 and early 1986, there is indicated to have been a slight increase in surface-to-500-mb precipitable water in the north temperate zone, but little change in the north subtropics or the world as a whole. Trends in precipitable water, based on data from two stations in the United States, are similar to trends in cloudiness.

Sunshine duration and cloudiness data for the contiguous United States were updated through the autumn of 1985. The tendency for a long-term increase in cloudiness and decrease in sunshine duration continues, but at a slower rate (about 0.4% per decade) than in the 1950s and 1960s. Furthermore, the tendency for increased cloudiness in autumn relative to other seasons is no longer apparent. The pattern of United States cloudiness increase was somewhat different at the time of the 1982–83 El Niño than at the time of the 1972–73 El Niño, the cloudiness increase occurring earlier with respect to El Niño in 1982–83.

Plans FY 1987

Tropospheric and stratospheric temperature data throughout the world will continue to be updated as an aid in judging whether the tendency for tropospheric warming and stratospheric cooling, i.e., an increase in lapse rate, signifies an early stage of a "greenhouse effect."

The humidity data will continue to be updated. When 2 years of humidity data are available, a detailed analysis will be made to determine whether it is worthwhile to obtain past humidity data for the 63 stations.

Sunshine duration and cloudiness data for the United States will continue to be updated to see if the tendency for a long-term increase in cloudiness, and decrease in sunshine duration, continues. Cloudiness changes will be compared and combined with humidity changes as a further aid in judging the evidence for a "greenhouse effect."

AEROSOLS AND RADIATION

Accomplishments FY 1986

The error to Umkehr measurements caused by stratospheric aerosols was determined from an analysis of concurrent Umkehr and lidar data. The results of this analysis compared quite favorably

with results from a previous empirical analysis and results from a theoretical investigation. The Mauna Loa data set is the only one of its kind in that both aerosol and Umkehr data were obtained at the same site, the range of stratospheric aerosol optical thickness was large compared with previous volcanic eruptions, and the number of concurrent data sets is large. The results greatly improve the credibility of theoretical calculations for correcting Umkehr measurements using data contributed from a world lidar network of eight stations.

To reduce lidar measurements of stratospheric aerosol in terms of optical thickness, the extinction-to-backscatter ratio must be known with reasonable accuracy. Concurrent lidar and ground-based sunphotometer data obtained at Mauna Loa provide a data set that can be used to solve for the extinction-to-backscatter ratio. An analysis of these data showed that the ratio changed from late 1982 to 1984, going from a low of about 40 to a high of 55 during the later part of this time period. Computations of the ratio using Mie theory and aerosol size distribution data obtained in situ by aircraft and inversion of sun photometer spectral extinction measurements produced results consistent with results from the lidar and sunphotometer data analysis. The results of the present work greatly improve our understanding of properties of stratospheric aerosols and our methods to observe these aerosols using the lidar technique.

The routine aerosol measurement program at the four GMCC observatories consists of the continuous determination of the aerosol scattering extinction coefficient and measurement of condensation nucleus (CN) concentrations. A nearly continuous data record now exists for Barrow since 1976, Mauna Loa since 1974, Samoa since 1977, and South Pole since 1974. A newly constructed four-wavelength nephelometer was installed at Mauna Loa to replace the older model that had been operating since 1974.

The seasonally averaged effect of clouds on downward solar irradiance at all four GMCC observatories was determined by comparing continuous observations of global irradiance with modeled and observed clear sky values. The results ranged from a 40% reduction in solar irradiance due to clouds at Barrow in the summer (July–September) to only a 13% reduction at Mauna Loa during January–March. These conclusions were based on 8 years of edited data.

Extremely high aerosol optical depths (0.7 at 500 nm) were detected in the vicinity of Barrow during April 1986. Because the measurements were made on board an aircraft, the vertical structure of the aerosol could be determined. Virtually all the aerosol was in the lower troposphere and exhibited substantial horizontal variability. Because of the dense concentration of the aerosol and the nearby eruption of a volcano we are uncertain about the origin of the aerosol.

Approximately 37 station-years of turbidity data have been acquired since the upgrade of the turbidity network in 1983. New data processing software and procedures have been implemented, and data for February 1983 to February 1985 were reduced in final form for 10 of the 14 stations now in the U.S. network. Four new stations were added to the network in FY 1986.

Of the 50 NOAA two-wavelength, handheld sunphotometers in GMCC's possession, 30 are deployed at baseline stations, in the U.S. network, or at cooperating stations. Sixteen of the remaining 20 were readied for deployment in an expanded U.S. network. Nine Noll Mainz–II sunphotometers were procured for use in the Automated Dobson Network.

A contract was awarded to the Eppley Laboratory for new solar-tracking units to be used in the national network. Prototype units were received in late FY 1986, and the testing/evaluation period began. A prototype PC-based data acquisition system was received, set up, and operated with software developed by ARL.

The Solar Radiation Facility primary reference, an absolute cavity radiometer, was taken to the Sixth International Pyrheliometer Comparison (IPC VI) in Davos, Switzerland, during October 1985. This instrument now has a history of participation in three IPCs: 1975, 1980, and 1985. A second absolute cavity radiometer was also taken to Davos for IPC VI. This second instrument, a GMCC

reference, is the primary standard at the Mauna Loa GMCC Observatory and was a participating instrument in the 1975 IPC.

A new computer-controlled data acquisition system was designed and purchased for the Solar Radiation Facility. The new system will allow in-house processing of data and should speed up all aspects of the facility's operations after installation in early FY 1987.

The Arctic Gas and Aerosol Sampling Program (AGASP) is a cooperative research program designed to determine the distribution, transport, chemistry, aerosol physics, and radiative effects of the polar-wide air pollution phenomenon known as Arctic haze. Conceived, organized, and directed by NOAA, the project involves participants from the United States, Canada, Norway, Sweden, Federal Republic of Germany, and Denmark. Intensive field studies took place in March–April 1983 and 1986. The core field research program consists of airborne measurements tied to similar baseline station measurements at Barrow, Alaska; Alert, Northwest Territory; and Ny Alesund, Spitzbergen.

In the just-completed second field study (AGASP-II), the heavily instrumented NOAA P-3 flew three 10-h missions from the NOAA GMCC Barrow baseline station. It then flew to Thule, Greenland, where joint flights were conducted over the Canadian baseline station at Alert in conjunction with the University of Washington C-131 (carrying a downward-looking aerosol lidar) and the Atmospheric Environment Services (Canada) Twin Otter aerosol physics aircraft.

Overhead and upwind of the Barrow station, profiles of gases and aerosols were conducted from 30 ft above the surface into the stratosphere. Above Alert, four similar profiles were completed, two in conjunction with the Canadian Atmospheric Environment Twin Otter. The other two were preceded by flyovers of the University of Washington C-131, which mapped the haze layers from 18,000 ft to the surface prior to the NOAA P-3 profiles.

On the first flight in the Alaska portion of the program, the NOAA P-3 found and characterized a 50-mile-wide transport zone of pollution more dense than those observed on AGASP-I. This anthropogenic pollution contained up to 990 ng m^{-3} of soot carbon and produced optical depths of about 0.7 to 0.8. This same haze subsequently passed over the Barrow baseline station where it was extensively characterized. On the following 2 days the haze moved south over Fairbanks where the P-3 flew in it and the University of Alaska Poker Flats Observatory collected surface samples. The haze finally moved south over Anchorage and out to sea. This is the first well-documented study of Arctic haze traversing all of Alaska.

Over Alert, all three aircraft measured up to six distinct layers of haze, which were also observed by an upward-looking lidar based at Alert. These haze layers extended for hundreds of miles upwind of Alert, and some penetrated into the passage between Greenland and Ellesmere Island.

On other flights, the NOAA P-3 penetrated the stratosphere over Alaska where heavy loadings of fresh volcanic debris were collected. These materials bear the same mineral signature as the debris from Mount Augustine, which erupted the first week of the AGASP-II field program.

Plans FY 1987

Sunphotometers to measure aerosol optical depth at five wavelengths in the solar spectrum will be installed at all Automated Dobson sites. The measurements from these instruments will be used to characterize the aerosol optical effects at each site and improve the quality of the Umkehr measurements. Umkehr measurements are weakly sensitive to tropospheric aerosols, but about 10 times more sensitive to stratospheric aerosols. Five new multiwavelength instruments will be acquired for use at the baseline stations.

GMCC solar and terrestrial radiation measurements will be used to begin an investigation of the relationships between Earth Radiative Budget Satellite measurements and the surface radiation balance. The investigation is directed toward developing an understanding of clouds on the radiation balance, determining the range of simple physical characteristics of clouds that influence the radiation balance, and determining the long-term radiation climatology in the Boulder vicinity. The research

procedures established from this investigation could be applied to radiation balance investigations at other U.S. solar radiation sites. In addition, similar procedures might be applicable to the UV observations by the NESDIS SBUV system to estimate the UV radiation flux reaching the surface at any location on Earth.

Zenith-sky cloud detectors will be supplied to all Automated Dobson sites. These instruments will detect the presence of clouds with great sensitivity, thus providing a valuable set of ancillary data for judging the quality of an Umkehr measurement. Automated Dobsons will operate without an observer-operator to judge the condition of the zenith sky as part of the procedure for making Umkehr measurements.

An intensive aerosol chemistry experiment will be performed at the South Pole during the austral winter of 1987. The following will be measured or determined: (1) aerosol scattering extinction coefficient, using the GMCC four-wavelength nephelometer data; (2) small particle concentration, using the G.E. condensation nucleus counter; (3) small particle size distribution, using a diffusion battery apparatus; (4) carbon aerosol concentration, using an aethalometer; and (5) aerosol elemental concentration, using a stepping streaker apparatus and proton-induced x-ray emission analysis. It is expected that the results of this experiment will contribute to an understanding of large-scale transport processes in the troposphere to the South Pole.

Work will continue on compilation and analysis of the radiation record acquired at Mauna Loa, which documents the effect of El Chichón. This 8-year record, which runs into 1986, shows the complete 4-year decline of the aerosol influence on radiation measurements at Mauna Loa.

A detailed analysis of U.S. network turbidity data will begin. Research will focus on the observable effects of El Chichón and the climatology of turbidity in the United States. Efforts to overcome the problem of calibration drifts due to filter degradation will continue. The period between calibrations will be shortened in an attempt to improve the accuracy of data collected.

Up to 22 additional two-wavelength sunphotometers will be deployed at the solar radiation network sites not yet a part of the U.S. turbidity network. As many as 10 new two-wavelength instruments will be built to accomplish the expansion. The NOAA-designed, five-wavelength, precision sunphotometers will be placed into service to collect high-quality data at Mauna Loa and other sites and will serve as standards for calibration of the network instruments.

The Solar Radiation Facility's new computer and data acquisition system will be delivered and installed in early FY 1987.

Recalibration of network sensors will begin again after the data acquisition system is installed, and after instrument tables are constructed on the roof of the RL-3 building in Boulder.

Testing and evaluation of the new national network prototype solar trackers is scheduled. If the prototype is accepted, the first 15 units can be produced and made available for installation at selected network sites.

The analysis of the AGASP-II data will continue into 1988. No new AGASP flights are currently planned.

CARBON DIOXIDE

Accomplishments FY 1986

The concentration of atmospheric CO_2 was measured continuously at Barrow, Mauna Loa, Samoa, and the South Pole. It was found that the average level of CO_2 at these four sites during 1985 was 345.1 parts per million (ppm) of dry air. This represents an increase of 1.2 ppm over the previous year. The 1984 continuous CO_2 data have been archived with the World Meteorological Organization (WMO). About 4500 samples from the flask sampling network (26 remote or clean air sites) were analyzed. The flask data from 1968 to 1984 have been archived with WMO. An interesting feature of

the 1985 flask data is that the characteristic equatorial bump in the north-south concentration profile was very much weakened this year. The mean annual growth rate recorded in the flask data agreed with the continuous analyzers to within 0.1 ppm.

In support of the continuous and flask sampling programs, about 200 CO_2 -in-air reference gas calibrations were performed. A new infrared CO_2 analyzer (a Siemens Ultramat), with significant improvements in precision and stability, was installed for the calibration work. A manuscript describing the entire GMCC CO_2 calibration history, which includes the results of all calibrations, was prepared.

At Mauna Loa, measurements of CO_2 and CH_4 were performed by gas chromatography from October until March. The CO_2 data compared favorably with the infrared analyzer data. The high-frequency CH_4 measurements showed systematic variations occurring on time scales of hours to days. These variations, which appear as scatter in the CH_4 flask data, are probably due to variations in atmospheric transport and the spatial variablity of sources and sinks of CH_4.

Vertical atmospheric profiles of CO_2 and CH_4 were measured during AGASP II flights over the Arctic. The concentrations of CO_2 and CH_4 were highly correlated with each other and with Arctic haze indicators such as condensation nuclei. Five out of six profiles showed elevated concentrations of CO_2 and CH_4 from 1 to 5 km above the surface. Preliminary analysis suggests that these observations are the result of long-range transport of anthropogenic emissions to the Arctic.

We participated in the Equatorial Pacific Ocean Climate Studies (EPOCS) and CO_2 Dynamics Cruise aboard the NOAA research vessel *Oceanographer*. Atmospheric CO_2 and CH_4, and pCO_2 and pCH_4 in ocean surface waters, were measured simultaneously. It appears that the CO_2 supersaturation of equatorial Pacific surface waters has weakened considerably, compared with other years.

A new objective statistical method was developed for analyzing flask data. It is based upon criteria for randomness of the residual differences between the data and fitted curves. Similar work is still in progress for the continuous data.

Plans FY 1987

Continuous monitoring of the atmospheric CO_2 concentration at Barrow, Mauna Loa, Samoa, and the South Pole will continue. Reports will be published describing the Mauna Loa, Samoa, and South Pole data. A Siemens Ultramat CO_2 analyzer will be purchased and installed at Mauna Loa.

Air samples for CO_2 analysis will be collected from the 26 sites of the CO_2 sampling network. The 1983 and 1984 flask data will be published, together with an analyis of the 1981–1984 results. Since the methods of sample collection and analysis did not change over this period, the set of measurements obtained is homogeneous. An experimental analysis in the laboratory will be made of factors that affect the quality of the flask sampling, such as humidity, UV light, and the type of valve. A report will describe in detail the local geography and meteorological conditions at the flask sampling sites.

References gas tanks will be calibrated with reference to the NOAA/GMCC secondary standards in use since 1979. The concentrations of these secondary standards have been determined in the WMO X85 mole fraction scale, maintained at the Scripps Institution of Oceanography. We will conduct an interlaboratory comparison of reference gas standards, sponsored by WMO. The 1984 and 1985 flask data will be reprocessed to take into account reference gas drifts and conversion to the X85 scale. The reprocessed data will be archived with WMO and the Carbon Dioxide Information Center (CDIC).

The continuous records will be used to evaluate sampling frequency and data analysis procedures of the flask sampling network.

A detailed comparison of the performance of the gas chromatograph and the infrared analyzer at Mauna Loa Observatory will be carried out.

We will participate in the joint U.S.-U.S.S.R. cruise and the EPOCS fall cruise, analyzing atmospheric CO_2, CH_4, pCO_2, and pCH_4 in surface waters. In addition, a regular flask sampling program will be started aboard commercial container ships crossing regularly between California and Australia.

Development work on the laser Raman scattering apparatus for measuring small variations in the atmospheric oxygen concentration will continue. The photon counting rates will be increased by an order of magnitude, by the installation of new optical fibers and new photomultipliers. Switching between sample and standard will be automated. More calibrations and stability tests will be performed.

TRACE GASES

Accomplishments FY 1986

The measurement of methane in flask air samples from 25 globally distributed network sites continued. A gas chromatographic system for in situ measurements of methane (60 samples per day) was installed at Barrow in late January 1986. A similar system was acquired for installation at Mauna Loa and is currently undergoing tests in Boulder. A sensitive detector for carbon monoxide was successfully interfaced to the gas chromatograph used for the analysis of flask air samples from the network, thus allowing the concurrent measurement of three species (methane, carbon monoxide, and hydrogen) from a single sample of air. Aircraft sampling to obtain monthly vertical profiles of methane (and other trace gases) in the troposphere began in July 1986.

Atmospheric measurements of two halocarbons—F-11 (CCl_3F) and F-12 (CCl_2F_2) —and (N_2O) continued at NOAA/GMCC baseline observatories located at Point Barrow, Niwot Ridge, Mauna Loa, American Samoa, and South Pole. Two flask samples were collected weekly at each station and returned for analysis in Boulder by electron capture gas chromatography (EC-GC). Biweekly measurements were performed at South Pole with an EC-GC by station personnel.

A fully automated EC-GC system was installed in June 1986 at American Samoa for measuring N_2O, and four halocarbons: F-11, F-12, carbon tetrachloride (CCl_4), and methyl chloroform (CH_3CCl_3). These data will be compared with concurrent flask sample data and our existing baseline data base. One goal under the Radiatively Important Trace Species (RITS) program is the complete automation of the sampling and analysis of the selected halocarbons and N_2O at each baseline station.

The interference of carbon dioxide (CO_2) with the measurement of N_2O by EC-GC detection was quantified, and our existing data base was corrected for this interference. A new method for eliminating this CO_2 interference was tested successfully in the laboratory.

A gas calibration facility was installed that uses gravimetric techniques traceable to the kilogram scale maintained at the National Bureau of Standards (NBS). Comprehensive standards for N_2O and the four selected halocarbons in air were prepared both at NBS in Gaithersburg, Maryland, and NOAA in Boulder, at the parts-per-billion (ppb) and parts-per-trilion (ppt) levels. These new standards are being compared against other international standards.

We also maintained collaborative efforts with Woods Hole Oceanographic Institution and Oregon State University. Specifically, this interaction involved analysis of N_2O and NH_2OH data and consultation in the development of an automated gas chromatograph for analysis of N_2O in seawater.

In addition to the continuing monthly stratospheric balloon-borne water vapor soundings made in Boulder, two successful soundings were made in American Samoa. The minimum mixing ratio of 2 ppmv at 17.5 km at Samoa is slightly lower than the lowest value measured at Boulder during the 5-year record of measurements. The stratospheric water vapor soundings continue to have an important role in the validation of the Stratospheric Aerosol and Gas Experiment (SAGE II) satellite water vapor measurements.

Plans FY 1987

Measurements of methane in flask air samples from the network will continue. A gas chromatographic system will be installed at Mauna Loa to provide in situ measurements of methane. Monthly vertical profiles of methane in the troposphere will continue to be measured. The first year of in situ methane data from Barrow will be reported. Various types of flasks will be evaluated for their suitability as containers of typical atmospheric levels of carbon monoxide in air. Gravimetric standards of carbon monoxide in air, at levels similar to ambient atmospheric concentrations, will be prepared and evaluated.

Automated EC–GC systems will be installed at the Mauna Loa and Point Barrow observatories for the measurement of N_2O and the four selected halocarbons. The EC–GC systems will be upgraded to measure N_2O separately from the halocarbons, without the CO_2 interference, at each station.

We plan an intercomparison of the RITS data and gas standards with data and standards of the Global Atmospheric Gas Experiment (GAGE) worldwide network, which is sponsored by both the Chemical Manufacturers Association and NASA.

The spatial resolution of N_2O and halocarbon measurements in the atmosphere could be increased by using the extensive NOAA/GMCC CO_2 flask sampling network. To achieve such improvement, the speed of analysis from the EC–GC system must be increased and a new flask container must be found. An automated EC–GC system for handling flask samples will be installed in Boulder to improve the analysis of flask samples. Research on the elastomer-free "generic" flask for all trace gases measured in GMCC programs will be conducted.

Participation of GMCC staff during a joint U.S.-U.S.S.R. cruise in the Pacific Ocean is anticipated. The purpose is to measure the latitudinal gradient of N_2O in the atmosphere and in surface sea water. These data would be valuable in calculating the oceanic flux of N_2O into the atmosphere.

An infrared gas cell for measuring the absorption cross sections of halocarbons at low temperatures, which was recently transferred from NBS in Gaithersburg, will be set up and used on a Fourier Transform Infrared (FT–IR) spectrometer in the Boulder area. These absorption cross sections are used by atmospheric modelers to predict the "greenhouse" warmings from trace atmospheric species.

Stratospheric water vapor soundings will be made monthly in Boulder. In addition, soundings are planned for January in American Samoa to correspond to the time of minimum tropopause temperatures in the western Pacific. The stratospheric water vapor soundings in Samoa will be part of the ongoing SAGE II satellite validation effort.

DATA ACQUISITION AND METEOROLOGICAL SUPPORT

Accomplishments FY 1986

The instrumentation Control and Monitoring System (CAMS), tested and installed during the previous fiscal year, proved to be a very reliable solution to the data acquisition needs at the GMCC observatories. Less than 1% of the total number of hours per unit was lost because of power outages or equipment failures. Data quality was also enhanced through the use of real-time displays that show calibrated values and printouts of important parameters. Some minor errors were detected in the code and the methods used to display data. These were corrected in the CAMS that is dedicated to the operation of the CO_2 analyzer. Revised memory and operations manuals were sent to the stations. Similar work on the Meteorology-Ozone CAMS is in the testing phase.

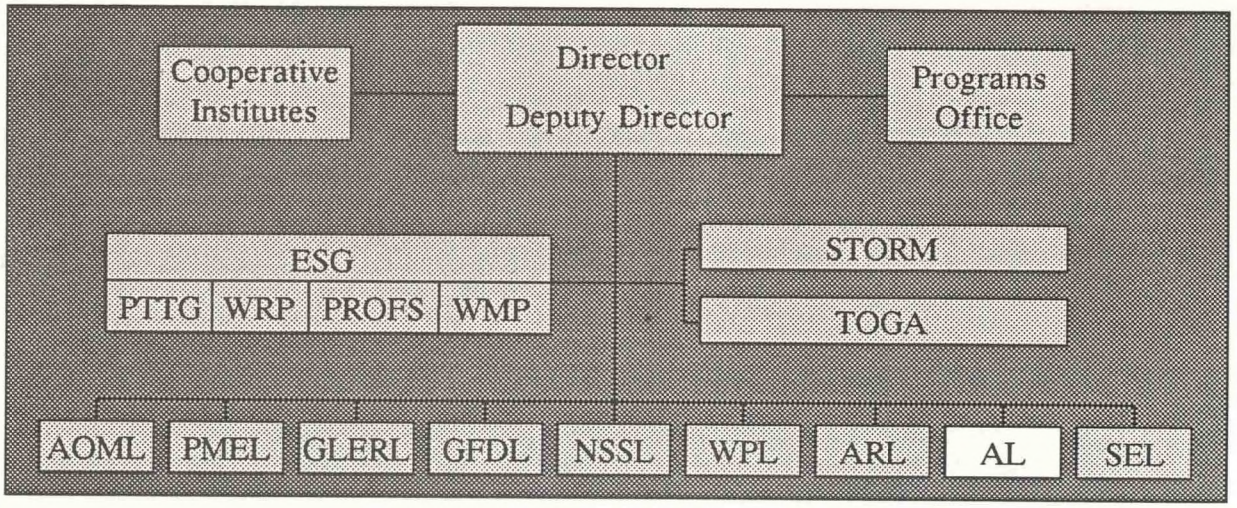
The meteorological variables—wind, station pressure, air temperature, temperature gradient, dew point temperature, and precipitation amount—are measured on a continuous basis at all GMCC observatories. The measurements are used to identify flow from local pollution sources and changes in air mass, and as a means of referencing gas, particle, and solar radiation measurements to standard atmos-

pheric conditions. With the exception of the dew point sensor, which is difficult to operate at cold temperatures, all sensors operated without difficulty. The only addition to the program was the tipping-bucket rain gauges to measure precipitation amounts. Hourly average amounts of precipitation are computed by CAMS.

For the past 6 years, GMCC has been developing a kinematic transport model to make possible the computation of air mass trajectories in both the forward and back directions, to study the influence of various source regions. The model is an adaptation of the ARL transport model. The most widely used version of the model estimates the back trajectories along standard isobaric surfaces for a period of 10 days. Such back trajectories were used to identify the source region's influence on the precipitation chemistry background-monitoring sites. Back trajectories on isobaric surfaces were also computed for each GMCC baseline station beginning every 12 hours for 1985 and the first 3 months of 1986. In support of the AGASP II study, back trajectories along isentropic surfaces were computed for those times when large discontinuities in the aerosol population were observed. Also in conjunction with this study, forward trajectories along isentropic surfaces were calculated for the times of known release from Mount Augustine.

Plans FY 1987

- Complete the revision, testing, and documentation of CAMS software.
- Transfer the management of the GMCC data base from the CYBER 750 to the ERL VAX.
- Explore methods of producing cross-section and time-section analyses by computer to improve the interpretation of monitoring data at the GMCC observatories.
- Complete the analysis of meteorological conditions and the associated flow influencing the gas and aerosol measurements made during the AGASP II study.
- Complete the construction of a stair-access sampling tower at Mauna Loa; begin a study of the influence of local structures on the wind measurements using the tower-top winds (40 m) as a reference.



AERONOMY LABORATORY
Boulder, Colorado
Daniel L. Albritton, Director

The Aeronomy Laboratory (AL) conducts research on chemical and physical processes of the Earth's atmosphere to advance the capability to monitor, predict, and control the quality of the atmosphere. The research concentrates on the stratosphere and troposphere, but also involves the mesosphere and thermosphere.

The research methods involve both in situ and remote measurement of critical atmospheric parameters, including chemical composition and dynamic properties such as wind velocity, turbulence, and wave motion. Theoretical programs in atmospheric photochemical modeling and in atmospheric dynamics and transport support the observation programs. An experimental laboratory chemical kinetics program supports the theoretical photochemical modeling program and also supplies input for the development of new atmospheric monitoring and measurement technology.

The research of the Laboratory is accomplished by seven interactive programs: Atmospheric Sampling, Optical Aeronomy, Theoretical Aeronomy, Atmospheric Chemical Kinetics, Atmospheric Dynamics, Tropical Dynamics and Climate, and Atmospheric Waves and Turbulence Theory.

The major focuses of research are Air Quality and Climate.

ATMOSPHERIC SAMPLING

The origin of the Atmospheric Sampling program lies in the recognition that human activities may inadvertently pose a threat to the Earth's stratospheric ozone layer, which serves as a shield against harmful solar radiation. The Atmospheric Sampling program was begun to address this critical problem. Balloon-borne methods were developed to measure the abundance of chlorofluoromethanes at the altitudes in the stratosphere where these species are significantly photodissociated into reactive chlorine atoms. These first-of-a-kind observations supported the theoretical predictions concerning the photochemistry of these compounds and hence the predictions of the potential adverse effects on stratospheric ozone.

Since that beginning, the scientific efforts of the Atmospheric Sampling program have followed the approach used in these initial stratospheric studies. Namely, problems are selected that combine

significant new scientific research with national or global atmospheric questions of environmental importance. The instruments and techniques required in these studies are generally conceived, designed, and developed within the program and are subjected to rigorous laboratory and field validations. The subsequent field application of these instruments and techniques employs a variety of platforms: balloons, stratospheric and tropospheric aircraft, ships, vans, and semipermanent ground stations.

The experience, skills, and interests of the group have expanded considerably since the stratospheric ozone studies and now encompass a broad range of topics in atmospheric chemistry and dynamics, which include the following:

- The tropospheric photochemical cycles responsible for the production and destruction of global ozone.
- The stratospheric/tropospheric exchange processes that are factors in regulating stratospheric and tropospheric chemistry and climate.
- The transport, transformation, and deposition processes involved in acid deposition.
- The natural emissions that contribute to atmospheric acidity and alkalinity.

Several key environmental issues are being addressed: stratospheric ozone depletion, acid deposition, global ozone and oxidant production, and climate alteration.

Accomplishments FY 1986

AIRCRAFT MEASUREMENTS OF GLOBAL NITRIC OXIDE DISTRIBUTIONS

Nitric oxide (NO) plays an important role in controlling tropospheric ozone (O_3). In addition to being a radiatively active trace gas that influences climate, O_3 also controls the lifetimes and abundances of most other trace gases because it initiates many chemical processes in the atmosphere. Therefore, NO indirectly controls the abundances of most reactive trace gases in the atmosphere.

However, the global distribution of NO has not been well characterized, chiefly because of the difficulty in obtaining reliable measurements of the small amounts that occur in the remote areas of the globe. In collaboration with the National Center for Atmospheric Research (NCAR), we have developed airborne NO instruments that have very low detection limits and are not subject to interference from other gases. Their accuracy and precision have been demonstrated both in the laboratory and in field trials over the past few years. These instruments are now being applied in a series of aircraft missions to improve definition of the global NO abundances.

Specifically, in collaboration with NASA, aircraft flights were made in the region between the California coast and Hawaii. It was verified that NO vanishes at night, which is a feature of its photochemistry that has been long predicted but never before unequivocally demonstrated. Furthermore, it was shown that NO increases with altitude, underscoring the dominance of the stratosphere as the source of NO in these remote areas. Finally, it was observed that NO could be produced in significant abundance by lightning. For this large portion of the globe, these data indicate that the NO abundance is sufficiently low that a net photochemical destruction of ozone should be occurring, which is an important factor in understanding the global ozone budget.

PHOTOCHEMICAL PRODUCTION OF OZONE BY NITROGEN OXIDES

An important input to the global ozone budget is the photochemical production of ozone from elevated NO and nitrogen dioxide (NO_2) emissions primarily from continental areas. An understanding of this photochemical source is a key part of unraveling the origin of suspected increasing abundances of ozone in the troposphere, where it has a "greenhouse" role, initiates many chemical reactions, and is toxic at elevated levels.

Production of ozone has been addressed by studying the relationships between the nitrogen oxides (NO_x = NO + NO_2) and ozone at Niwot Ridge, Colorado, over several seasons. It is observed that there is very little dependence of ozone on NO_x abundance during the cold, dry winters at this mountain site. In contrast, during the summer, a daily late-afternoon increase in ozone is found to correlate strongly with the NO_x levels. The consistency of these observed and model-calculated daily summer ozone increases suggests that the average ozone production in rural areas may be predicted if NO_x is known.

Hence, this dependence of ozone production on NO_x allows a crude, initial estimate of total ozone production. For the United States, it is estimated that approximately 20 times more ozone is made photochemically than is transported downward from the natural source in the stratosphere. For the Northern Hemisphere, the ozone that is produced from anthropogenic precursors is possibly one-third of that generated from natural sources. Additional measurements of NO_x and other ozone precursors are required to refine these estimates.

ASSESSMENT OF TECHNIQUES FOR MEASURING THE NITROGEN OXIDES

Different methods are being used to measure the abundance of the nitrogen oxides in the atmosphere. If a consistent picture of global distributions is to be formed from these data, the respective reliabilities of the methods must be known. As part of a series of assessments of experimental methods, we carried out a ground-based intercomparison of techniques used to measure two of the nitrogen oxides.

Specifically, two different methods were examined for measuring nitrogen dioxide (NO_2) and two for total reactive nitrogen (NO_y). All the methods rely on the conversion of NO_2 and NO_y to NO, which is then detected by chemiluminescence. In the case of NO_2, ferrous sulfate and photolytic conversion techniques were compared. For NO_y, molybdenum oxide reduction and gold-catalyzed reduction by carbon monoxide were compared. The key question was whether the conversion was specific and efficient.

The intercomparisons were carried out in early 1986 near Boulder, Colorado, and involved NOAA and University of Maryland instruments. An NCAR scientist served as the independent reviewer of the "double-blind" measurements. In addition to side-by-side measurements of ambient air, "spikes" of potentially interfering species were added.

The results show that the two methods for NO_y are equally good over wide ranges in concentrations. For NO_2, however, the ferrous sulfate technique suffers from a major interference from peroxyacetyl nitrate (PAN) and to a lesser extent from other species; that is, the method is not specific for NO_2, but rather converts non-NO_2 species also. This has a profound implication to air quality research since the overwhelming majority of NO_2 measurements are made with the ferrous sulfate method and hence give erroneously large values.

INSTRUMENTATION FOR ANTARCTIC OZONE EXPEDITION

One explanation that has been proposed to explain the dramatic loss of stratospheric ozone over Antarctica in the austral spring is an accelerated loss due to anthropogenic chemical species. To test this and other hypotheses, a joint NASA, NOAA, and NSF expedition carried several existing types of apparatus to McMurdo Station to observe several chemical species.

The NOAA instrument is a diode array spectrometer with unparalleled sensitivity and stability for measuring the small absorptions that the nitrogen oxides introduce into sunlight or moonlight. In the few-month period that the expedition had to prepare for the trip, two spectrometers were readied for the environment anticipated and were tested in Colorado. Currently, the messages from McMurdo report that both are operating as expected. The data set should provide detailed insight into the chemistry of the Antarctic stratosphere.

STRATOSPHERIC REACTIVE NITROGEN STUDIES

In addition to its role in atmospheric chemistry, NO_y is also a tracer of atmospheric motions. Since it is the sum of the reactive nitrogen compounds, it is, in the absence of deposition, a semi-conserved quantity. In collaboration with NASA, we are employing the ER-2 stratospheric aircraft to examine processes of exchange between the stratosphere and the troposphere. One of the tracers employed in the experiment is NO_y. The major focus of the experiment is a study of processes over Australia/Micronesia in early 1987.

The test flights have provided an opportunity to measure for the first time the NO_y vertical distribution in the lower stratosphere (up to 20 km). The maximum values observed near this altitude were 5 to 10 parts-per-billion by volume. This range is in accordance with the sum of the separately measured values of earlier and diverse studies and compares favorably with theoretical predictions for these middle-latitude observations.

BIOLOGICAL FACTORS IN NATURAL SULFUR EMISSIONS

Our field program in 1985 demonstrated that vegetation contributes substantially to the budget of sulfur compounds emitted from natural sources. In particular, this study detected the production of volatile sulfur compounds in the presence of growing vegetation. Identifying and quantifying the factors that shape these emissions will help determine the biogenic mechanisms responsible and lead to improved estimates of the sulfur flux into the atmosphere.

Although several studies have revealed an exponential dependence of sulfur flux upon temperature, no systematic tests of the independent effects of varying light intensity were possible under field conditions. Hence, a collaborative laboratory investigation with the University of Colorado was undertaken to determine what factors control sulfur emissions from various types of vegetation. Using a flux chamber method, we observed several sulfur emissions from corn, alfalfa, and wheat to change by as much as a factor of 4 at constant temperature as illumination was varied from zero to mean summer daytime levels. Furthermore, by varying the carbon dioxide (CO_2) content of the chamber flush gas, it was shown that the observed sulfur fluxes are not the result of CO_2 stress. Growing these "crops" through holes in a Teflon soil-covering film allowed us to determine, separately, soil and foliage emissions and to substantiate the light-dependent uptake of COS by growing vegetation observed in previous field studies. The data are being used to parameterize the inventory of sulfur emissions from natural sources.

DIETHYLAMINE IN TROPOSPHERIC AEROSOLS

Historically, ammonia is the only basic compound that has been given much attention in tropospheric studies. However, other bases would be of considerable interest, both in terms of their impact on tropospheric chemistry and their potential neutralization of atmospheric acidity. Amines are stronger bases than ammonia and form interesting products in the reactive tropospheric environment. However, it is difficult to assess the role of amines in tropospheric processes, owing largely to the lack of measurements of amines in the atmosphere.

Diethylamine has been detected in tropospheric aerosols collected at two sites: Niwot Ridge, Colorado and Mauna Loa, Hawaii. Concentrations as large as 200 parts per trillion by volume were observed, always accompanied by a strong diurnal variation. The lack of correlation of the abundance with anthropogenic species makes the identification of the source of this amine difficult. These observations do, however, demonstrate that the amines could have a substantial role in the chemistry of the troposphere.

Plans FY 1987

Studies of the nitrogen chemistry of the boundary layer are continuing with measurements in an eastern environment for the first time. The sites are in central Pennsylvania: Rock Springs, an agricultural station, and Scotia, a forested area nearby. These studies are an extension of earlier studies at Niwot Ridge, in the Colorado mountains, and at Point Arena, on the California coast. Thus, these eastern measurements will test our understanding of nitrogen-related ozone and acid production in the higher chemical levels of the polluted eastern United States.

The soil emission of NO and NO_2 will also be studied in Pennsylvania. The data will complement those obtained earlier in Colorado and will substantially add to our understanding of natural nitrogen emissions in the United States. This study will be the first phase of assembling a national inventory of acid-related emissions that can be used to compute the natural component of acidic emissions in the United States.

Ammonia (NH_3) is an important trace chemical in the lower atmosphere. Although ammonia is reasonably abundant, available measurement techniques have not proved entirely satisfactory. We have developed an instrument for gas-phase ammonia measurements. It collects NH_3 on an oxidized molybdenum surface; the collected NH_3 is thermally desorbed directly as NO, which is monitored with a chemiluminescence detector. The instrument has a linear response to NH with a detection limit near 100 pptv for a 30-min sample time. Interference from NO, NO_2, and nitric acid (HNO_3) is negligible. However, the technique responds to amines as well as NH_3, and thus represents a total amine collector. Preliminary field measurements were made of gas phase NH_3 (+ amines) at a grassland site west of Boulder, Colorado. The technique and instrument will be the basis of a series of survey measurements aimed at assessing the role of such basic compounds in neutralizing atmospheric acidity.

The NO_y technique will be added to the airborne NO and NO_2 instruments and used, in collaboration with NCAR, on a series of aircraft flights. A NASA aircraft will carry a suite of instruments that will focus on the reactive nitrogen distributions and reactions in the troposphere and on instrument reliability. The reactive nitrogen species to be studied are NO, NO_2, HNO_3, PAN, and NO_y. In addition, O_3, NH_3, CO, nonmethane hydrocarbons, and solar flux will be measured, as well as meteorological parameters. For most of these reactive nitrogen species, two to four instruments employing different methods will be aboard. Thus, in addition to providing the most detailed examination to date of the reactive nitrogen species in the free troposphere, this study will be able to evaluate, by means of intercomparison, the reliability of NO_2, HNO_3, PAN, and NO_y measurements.

The study of organic acids and bases that have been observed in different regions will continue. The studies, which have concentrated on liquid and aerosol phases, will be extended to include gas-phase measurements. Preliminary results indicate concentrations of formic acid up to nearly 1 ppbv and smaller concentrations of other gas-phase organic acids. A program to measure aldehydes, which are possible precursors of the organic acids, has been initiated also.

The differential absorption lidar technique has been developed to measure ozone in the free troposphere. There is currently no fully acceptable method to do so, despite the need to assess potential human alteration of this important climatic and chemical species. Two lasers are being used for the differential absorption method, one providing the wavelength that is absorbed strongly by ozone and the other providing the wavelength that is not. Tunability is used to generate a signature that will verify that the absorption is due to ozone alone. Aerosol densities, which could cause an artifact absorption, will be monitored with a separate wavelength. Range scanning of the lidar will define the altitude variation. It is expected that a profile up to 12 km can be obtained in minutes with a precision of 5% and an accuracy better than 10%. Assessments with theoretical models at the Aeronomy Laboratory and the Geophysical Fluid Dynamics Laboratory indicate that this will be adequate to define the ozone variance in the troposphere. The two laser systems are operating at Fritz Peak Observatory, a mountain location west of Boulder and above metropolitan Denver's aerosol layer. Preliminary optical tests are

under way and we plan initial atmospheric tests by 1987. Intercomparisons with high-accuracy balloon-borne ozone instruments will be followed by regular measurements.

In addition to transfer of constituents between the stratosphere and troposphere in the extratropics by tropopause folds associated with jets, considerable transfer is also occurring in the tropics. The most intriguing transfer is by large cumulonimbus clouds and/or thermally forced mean circulations. The stratosphere/troposphere exchange program in which the group is involved is considering all of the transfers, the tropopause fold study conducted with the U–2 aircraft in the spring of 1984 having been the initial campaign. The new studies will be made with the ER–2, a more advanced stratospheric research aircraft, and with more sophisticated sensors. The Atmospheric Sampling group has developed sensors for water vapor, water vapor and ice, ozone, and total reactive nitrogen (NO_y). The test flights for these are complete. The flights in the early part of 1987 will focus on cloud processes north of Australia. The goal will be to characterize both the rapid vertical transport by large cumulonimbus clouds, which form their anvils in the lower stratosphere, and the slower, larger-scale transport attributed to mean circulation.

OPTICAL AERONOMY

The Optical Aeronomy Program uses spectroscopic measurements of the atmosphere as a tool for studying fundamental atmospheric processes such as energy balance, composition, and dynamics. The center for the observational program is Fritz Peak Observatory located at 8600 ft elevation in the mountains west of Boulder.

The major current activity of the program is studies of the lower atmosphere including both the stratosphere and troposphere, where the composition and chemistry have begun to receive major attention now that the fragility of the ozone layer and problems of pollution have become apparent. The lower atmospheric studies have generally used spectroscopic measurements of absorption by molecules. This approach exploits the extraordinary sensitivity of optical absorption for the detection and quantitative measurement of minute quantities of chemically important species in both the stratosphere and the troposphere. The location of the Fritz Peak Observatory has proved to be very favorable, particularly for troposphere studies, since the wind patterns allow us to study both the occasional downwind pollution from Denver and the extremely clean air during the normally westerly wind flow. We have also carried out measurements at many other locations, using platforms ranging from vans, ships, and aircraft to the Solar Mesosphere Explorer satellite.

Accomplishments FY 1986

The near-ultraviolet interferometer located at Fritz Peak continues to measure the column density of stratospheric hydroxyl (OH), the only OH column measurements being made anywhere. This series now extends for 10 years. Several features of the behavior of OH continue to challenge theory.

The observations of infrared molecular oxygen emission permit measurement of ozone at mesospheric altitudes where it cannot otherwise be determined. The observations revealed dramatic seasonal and short-term changes associated with upflow of hydrogen compounds from the underlying stratosphere. In effect, this permits a study of the upper boundary conditions of the stratosphere that are necessary for realistic modeling of its behavior.

We continued observations of the emissions of 0^+ ions in the upper thermosphere created by the absorption of solar ultraviolet light by oxygen atoms. The data directly determine the density of the atmosphere at high altitudes where the majority of satellite instruments can no longer make in situ observations. It is thus possible to follow the changes in upper thermospheric composition with season and geomagnetic activity.

Plans FY 1987

STRATOSPHERIC OH MEASUREMENTS

The near-ultraviolet interferometer that is currently at Boca Raton, Florida, is being relocated to Truk Island in the equatorial Pacific. The goal is to explore the interaction of tropical dynamics on the stratospheric OH densities. Before it is moved to Truk Island, the instrument will be set up at Fritz Peak in the fall of 1986, to make concurrent measurements with the interferometer there.

TROPOSPHERIC OH STUDIES

A major new effort to measure tropospheric OH is now under way at Fritz Peak. The method is to use long-path absorption over a 20.6-km light path from Fritz Peak to the Caribou Mine and back. A sophisticated array of retroreflectors has been installed in a new building at Caribou Mine at 9600 ft elevation on the Continental Divide. The 1-m^2 array demonstrates superior reflectivity and collimation properties. The use of retroreflectors also makes it possible to run a number of experiments simultaneously since each experiment sees only its own return beam. The XeCl laser output is very broadband and includes five Q and P branch OH rotational lines in its bandpass. The spectrograph is a new 2-m focal length echelle system, which will have a new echelle ruling and reticon detector systems that are under construction locally. The new system will spectrally resolve the individual atmospheric OH rotational lines. We expect to measure to approximately 3×10^5 cm^{-3} OH abundance in 1 min. Summer values of OH abundance are predicted to be approximately 5×10^6 cm^{-3} and winter values about 1×10^6 cm^{-3}.

MULTIPLE SCATTERING MEASUREMENTS

Recent theoretical analysis has demonstrated the importance of multiple scattering for interpreting daytime photochemistry. An accurate knowledge of the tropospheric and stratospheric radiation field is essential to verification of the theory and could potentially have a significant effect on tropospheric and stratosphere photochemistry. A 3-year program to address this problem is beginning. The first goal is to build instrumentation to measure the seasonal radiation field at Fritz Peak, and the second will be a series of U–2 research aircraft flights over regions of known albedo into the lower stratosphere (21 km) to measure the field as a function of altitude.

ANTARCTIC OZONE EXPEDITION

Our group is participating in an expedition to Antarctica to make spectroscopic measurements of ozone depletion there. The recently discovered "hole" in ozone is now a subject of keen scientific interest. Theories abound concerning solar cycle effects and anthropogenic chlorofluorocarbons. Our group, along with groups from the Jet Propulsion Laboratory, the State University of New York, and the University of Wyoming, hopes to obtain data to discriminate between theories and formulate more accurate ones. Our instrumentation will measure O_3, NO_2, NO_3, and OClO in near-real time with 15-min resolution.

THEORETICAL AERONOMY

The Theoretical Aeronomy Program undertakes theoretical studies of important atmospheric problems, constructs and uses computer models of the chemistry and dynamics of the atmosphere, and analyzes atmospheric data collected by the Laboratory or in collaborative experiments. The ultimate goal of the program is to attain an understanding of the composition, dynamics, and energy budget of the atmosphere that is sufficiently detailed to permit accurate predictions of trends. In recent years the

principal concern has been with problems related to the minor-constituent composition of the stratosphere and mesosphere (the middle atmosphere), deriving largely from the widespread practical concern with stratospheric ozone and its potential depletion by artificial pollutants. More recently, however, the activities of the group have expanded to investigate problems of tropospheric chemistry and tropical atmospheric dynamics, and the biosphere-atmosphere interaction is another important new research area. These new areas are expected to grow, in parallel with corresponding growth and shifts of emphasis in the experimental programs of the Laboratory. Most of the program's projects are developed and carried out in close collaboration with the Laboratory's experimental programs, or with other atmospheric research groups outside the Laboratory, including at present those at GFDL, NCAR, and the University of Colorado. These outside links are essential to the objectives of the program, and will be maintained and strengthened where possible in future years.

In addition to its own projects, the group has the important function of assisting other Laboratory programs on problems that require advanced computer programming techniques. This direct service function provides further coupling between this program and the more experimental side of the Laboratory.

Accomplishments FY 1986

TROPOSPHERE

Research in tropospheric photochemistry centers around acid deposition and tropospheric ozone. Acid deposition is a serious problem in the northeastern United States and eastern Canada. Precipitation with pH of 4.0 to 4.5 is quite common in these areas downwind of midwestern industry. Most of the anions contributing to the high acidity are $SO_4^=$ and NO_3^-, the precursors of which are SO_2 and NO_x ($NO + NO_2$). Tropospheric ozone has a central role in the photochemistry that controls the abundance and interaction of SO_2, NO_x, and other important atmospheric trace gases (e.g., CO, CH_4, and H_2S). The photochemistry and transport of acid material and ozone are closely related. There is increasing evidence that tropospheric ozone may have been perturbed by anthropogenic emissions of hydrocarbons and NO_x ($NO + NO_2$). Perturbation of tropospheric ozone may cause a chain reaction that could change the distribution of trace gases. Since ozone and CH_4 absorb infrared radiation in the window of CO_2 and H_2O absorption, the radiation budget in the troposphere, and thus the climate, may be altered. In addition, surface ozone may damage plants and may be a health hazard.

The Theoretical Aeronomy Program continues to be involved in these topics of research relating to tropospheric ozone and acid deposition:

- Development of a fine-resolution planetary boundary layer (PBL) model to simulate the transport and photochemistry of O_3, NO_x, and hydrocarbons, especially in the surface layer.
- Planning and interpreting measurements of NO_x, O_3, HNO_3, SO_2, and particulate NO_3^- and $SO_4^=$, in collaboration with the Atmospheric Sampling Program.
- Modeling the tropospheric ozone and NO_x distributions with a three-dimensional general circulation model, in collaboration with scientists at GFDL.
- Development of a mesocale air quality model for the Colorado Front Range, in collaboration with scientists at NCAR.
- Development of a combined liquid-phase and gas-phase photochemical model to study oxidation of NO_x and SO_2.
- Model studies of the distribution of NO_x and SO_2 that are produced from natural sources.

Comparison of model calculations with observed relationships among O_3, NO_x, and nonmethane hydrocarbons produced major advances in the understanding of the tropospheric O_3 budget and distribution. Using a new technique that evaluated the O_3 photochemical production by examining the Lagrangian behavior of the O_3 precursors, the O_3 production per NO_x molecule emitted was shown to be essentially independent of the season. In the winter the NO_x emissions due to human activities in the Northern Hemisphere far exceed the natural emissions; thus the dominant O_3 production may be anthropogenic. Since the O_3 lifetime in the winter in the middle latitudes is longer than 100 days, anthropogenic O_3 may be transported over most of the Northern Hemisphere. Previously, photochemical production of O_3 in the winter was considered negligible compared with the O_3 flux from the stratosphere. The long lifetime of O_3 in the winter enables anthropogenic O_3 to accumulate and thus contribute to the spring maximum observed over clean areas in the Northern Hemisphere. In the past, the spring maximum was considered to be primarily the result of stratospheric O_3 intrusion.

In the summer, O_3 from natural NO_x emissions may be more abundant than anthropogenic O_3 for the Northern Hemisphere as a whole. In the industrialized nations the latter source dominates. However, because the O_3 lifetime in the PBL is only about 10 days, near the surface anthropogenic O_3 may be limited to a regional area or to the middle latitudes at most. This possibility is supported by an observed long-term trend of O_3 at a clean GMCC station, Mauna Loa, which shows an increase of about 2% per year only in the winter and spring, whereas at a polluted station, Hohenpeissenberg, Germany, a similar increase has been observed for all the seasons.

The climatic effect of the estimated O_3 increase is still uncertain. This is because the climatic effect depends critically on the O_3 increase in the upper troposphere that is difficult to estimate. An evaluation by using a global circulation model with chemistry is needed.

It has been long realized that a change in column O_3 perturbs the tropospheric O_3 because of the change in UV penetration. However, we found that the change in tropospheric O_3 depends critically on the NO_x concentration. At high NO_x or in a polluted area where there is net O_3 production, a decrease in column O_3 will increase the UV penetration and thus increase tropospheric O_3 concentration. On the other hand, at a remote oceanic area where NO_x is so low that there is net O_3 destruction, tropospheric O_3 will decrease when column O_3 decreases. This finding may have important implications for the interpretation of the long-term trend of tropospheric O_3 because of the expected column O_3 reduction due to the release of chlorofluorocarbons.

Changes in the column O_3 will also affect tropospheric OH, which in turn will affect the concentrations of many reduced gases such as CH_4 and CO. We found that the change in OH was essentially independent of NO_x concentration. The estimated effect on CH_4, however, was small compared with the observed change.

Since the vertical transport has a crucial role in the long-range transport of pollutants, the mesoscale model was used to study the vertical transport of an inert tracer in the western United States under summer conditions. The initial distribution of the tracer was assumed to be uniformly mixed in the PBL. After 24 hours, about 50% of the tracer was transported above the PBL. Analysis of the mechanisms of vertical transport showed that three major processes (turbulence, large-scale advection, and orographic mixing) contributed about equally to the vertical transport. Contribution from other processes was negligible. However, transport due to convective clouds was not included in the model. It is expected that vertical transport due to clouds could be significant. We are testing several techniques to parameterize the cloud transport self-consistently.

MIDDLE ATMOSPHERE

Our chemical and dynamical modeling studies of the middle atmosphere are aimed at achieving a better understanding of the factors controlling the distribution and variability of trace constituents such

as ozone, methane, and nitrogen dioxide. Collaboration with NCAR continues to be an essential part of this effort.

Over the past year, the publication of the observation of anomalously low ozone densities in Antarctica (the ozone "hole") has stimulated an important part of our theoretical and observational work. Observations of total ozone by the British Antarctic Survey show that the total-ozone column over Antarctica has decreased by 30–50% over the past 15 years or so during the spring season. No such obvious perturbation is observable in other seasons, or at other than the very highest latitudes in the Southern Hemisphere. We analyzed available balloonsonde data from the Japanese Antarctic research station at Syowa to show that the perturbations occur largely over heights of 10–20 km. The data also show that homogeneous gas-phase chemistry as now understood cannot explain the observed depletions. A unique feature of the Antarctic lower stratosphere is its high frequency of polar stratospheric clouds, providing a reaction site for possible heterogeneous reactions. Several studies have shown that the reactions

$$HCl + ClONO_2 \rightarrow HNO_3 + Cl_2$$

and

$$H_2O + ClONO_2 \rightarrow HNO_3 + HOCl$$

are extremely fast on laboratory surfaces. We showed that these reactions might liberate large amounts of active chlorine from the chlorine reservoirs HCl and $ClONO_2$, thereby leading to potentially large ozone losses similar to those observed. These reactions also must remove a substantial fraction of the NO and NO_2 from the Antarctic lower stratosphere. Thus, further information on other constituents besides ozone, such as ClO, NO_2, and HNO_3, is required to understand the cause of the ozone depletion. The Aeronomy Laboratory's Theoretical, Optical Aeronomy, and Atmospheric Sampling groups will participate in the National Ozone Expedition (NOZE) at McMurdo Station, Antarctica, Aug.–Nov. 1986, as part of a program for gathering such data. The program is discussed further under Plans.

Satellite data analysis is another major area of study. The LIMS (Limb Infrared Monitor of the Stratosphere) experiment provided large amounts of data on NO_2, HNO_3, and ozone. The data show that nitric acid in northern winter at high latitude displays behavior that is not predicted by current chemical theory. In particular, it was found that nitric acid abundances along parcel trajectories increased over time during the polar night. Chemical theory would predict that nitric acid can increase only in the sunlit atmosphere. Thus, an anomalous source of nitric acid during winter was suggested. We studied the behavior of LIMS NO_2 data in high-latitude summer. These data provide information on the density of NO_2 for zenith angles from about 45° to 110°, and they represent a unique means of studying the diurnal variability of NO_2. We showed that the data display strong evidence for the importance of multiple scattering of solar radiation as it affects the density of NO_2, because of its role in the photolysis of NO_2. Further, a decay of NO_2 to form N_2O_5 could be clearly distinguished at zenith angles greater than 90°, and the rate of decay of NO_2 was shown to be in good agreement with theoretical predictions.

LIMS also measured stratospheric and mesospheric ozone. The LIMS instrument measured all species by infrared emission, and the data reduction was based on the assumption that the densities of the emitting states are in local thermodynamic equilibrium (LTE) with the ground state. This implies that the emitting vibrationally excited molecules are populated only by collisional excitation. In the mesosphere, vibrationally excited ozone can also be formed rapidly by the recombination reaction, driving the density of vibrationally excited molecules out of LTE.

We showed that this reaction is of substantial importance to the LIMS data above about 50 km, and that its effect on the diurnal variation of the measured ozone is as large as a factor of 2 near 70 km. We used the LIMS data to examine the radiative budget of the stratosphere. The LIMS ozone temperature and NO_2 and H_2O data were used as inputs to detailed numerical models of infrared cooling and ultraviolet and visible heating. The net radiative heating of the stratosphere was thereby

deduced on a monthly basis for the period over which LIMS data are available (November 1978–May 1979). These data will be significant for testing any numerical model of the dynamics of the middle atmosphere, wherein the heating rates are calculated a priori rather than based on observation. Further, they provide a basis for deducing the diabatic (heat-driven) circulation of the stratosphere. Theoretical studies suggest that the diabatic circulation is a good approximation to the advective transport taking place in the stratosphere, except perhaps in the winter at middle and high latitudes. We used our deduced net radiative heating rates to derive the mean meridional circulation on a monthly basis, and used this circulation to transport the "tracers" N_2O and CH_4. The comparison between the observed (from the satellite experiment) and modeled N_2O and CH_4 fields as a function of time provides a test of the accuracy of the transport description. We found that the tracers were rather well reproduced by the model, giving confidence in the radiative calculation and in the validity of this approach to transport modeling. In particular, the model reproduced the observed double-peak in N_2O and CH_4 in tropical regions, which is believed to be associated with the semiannual oscillation.

Data from the Poker Flat radar, which has been operated by the Aeronomy Laboratory since 1979, were used to obtain information on two important parameters of the high-latitude mesosphere—the concentration of nitric oxide, and the rate of photodestruction of the nitrate ion NO_3^- by sunlight. Wintertime mesospheric echoes recorded by the radar show a sudden enhancement before ground sunrise, caused by the release of electrons from negative ions by sunlight. The timing of this increase can be used to determine the effective wavelength of the solar radiation responsible for the effect, and hence to deduce the nature of the dominant negative ion. A time-dependent model of mesospheric ion chemistry was used to show that the nitrate ion was dominant most of the time, which in turn allowed an estimate of the concentration of NO. The results indicate that NO is present in the high-latitude winter mesosphere in considerably larger amounts than estimates have suggested.

There has been widespread interest recently in a controversial suggestion that transient decreases in the intensity of the airglow from atomic oxygen observed by the Dynamics-Explorer satellites is due to a steady influx of small "comets," composed mostly of ice, into the upper atmosphere. We used a one-dimensional model to show that the amount of mesospheric water vapor implied by this suggestion is far in excess of that observed, and we set observational constraints on the influx of water from extraterrestrial sources. Although a weak extraterrestrial source of water would actually improve the match between current models and observations, the influx cannot be more than about 0.03 times the influx proposed by the "comet" mechanism. This would be insufficient to cause the observed airglow depletions. Thus their explanation remains a mystery.

Plans FY 1987

TROPOSPHERE

Tropospheric modeling will be concentrated on two efforts. One concerns the vertical transport parameterization in the mesoscale air quality model, in particular the transport due to convective clouds. This transport process is probably one of the major mechanisms responsible for long range transport of O_3, NO_x, nonmethane hydrocarbons, and other pollutants. The other effort will use the mesoscale model to evaluate ozone production in the natural environment versus that from anthropogenic NO_x and nonmethane hydrocarbons sources. The model calculations will be done first for the western United States. The results from the model calculation will be analyzed to test the linearity in the relationship of O_3 and its precursors.

The Atmospheric Sampling group made measurements of NO, NO_2, O_3, nonmethane hydrocarbons, PAN, HNO_3, NO_3, and meteorological parameters at State College, Pennsylvania, in the summer of 1986. Our group will use the models developed over the last few years to interpret the data. Specifically, the ratio of HNO_3 or NO_3 to NO_2 will be analyzed carefully to deduce information on the

concentration of OH and the nighttime conversion of NO_x to HNO_3 or NO_3 through the following reactions:

$$NO_2 + O_3 \rightarrow NO_3 + O_2$$

$$NO_3 + NO_2 \rightarrow N_2O_5$$

and

$$NO_3 \text{ (or } N_2O_5) + H_2O \rightarrow HNO_3 \text{ or } NO_3^- \quad .$$

The nighttime reaction may have important implications on the O_3 production. The role of natural hydrocarbons in the O_3 budget will also be examined. Our preliminary model calculations indicate that in the rural area of the eastern United States natural hydrocarbons have a major role in the O_3 production. However, the NO_x precursor is mostly anthropogenic. The role of natural hydrocarbons in the photochemistry of acid deposition is probably also important. This will be evaluated in collaboration with scientists at NCAR.

MIDDLE ATMOSPHERE

The Aeronomy Laboratory will take two visible spectrometers to McMurdo Station as part of the National Ozone Expedition (NOZE). It is hoped that measurements of NO_2 and O_3 can be made simultaneously with this instrument by measuring scattered sunlight at a minimum; this will provide important information on the correlation (or lack thereof) between the two, which is important in elucidating the cause of the ozone hole. Further, if clear-sky conditions prevail there in early to mid-September 1986, the moon can be used as a light source for visible absorption. This will permit measurements of NO_3, and, if elevated levels of chlorine are related to the ozone anomaly, then OClO densities should also be measurable, providing an important check on the role of chlorine in the ozone depletion there. The measurements made during NOZE should be extremely valuable in constraining all theories of the cause of the ozone anomaly.

Modeling research on the stratosphere and mesosphere will also continue. In particular, we plan to couple the detailed radiative code used in our diagnostic study directly into our coupled two-dimensional chemical/dynamical model. This will enable us to explore the role of radiative coupling in the stratosphere, and to examine the role of perturbations in ozone and other species, such as CO_2. We also intend to study the chemistry of the OH Meinel bands in the mesosphere, and examine their dependence on season and latitude. Finally, the data analysis from McMurdo and other AL studies using the visible spectrometer will be carefully examined to understand the information content of ground-based visible absorption measurements. In particular, we hope to better understand the altitude information available with this technique.

ATMOSPHERIC CHEMICAL KINETICS

The primary activity of the Atmospheric Chemical Kinetics program is the experimental investigation of chemical reactions that are important in the atmosphere. Although the research is focused on the effects of anthropogenic chemical species, a second objective is to understand the natural, unperturbed atmosphere. The information obtained in this program includes the rate coefficients and mechanisms of chemical reactions, thermochemical and spectroscopic data, and values of photochemical parameters.

The chemistry of the stratosphere is of great interest because of the potential for humans to alter the ozone layer inadvertently, with disastrous consequences. First, the possibility of an ozone reduction from exhaust chemicals released in stratospheric flights of supersonic aircraft was considered. This brought worldwide attention to the potential for a global problem, an increase in biologically harmful

UV radiation at the Earth's surface, caused by the reduction in stratospheric ozone. Later, chlorine-containing halocarbons and nitrogen fertilizers were identified as potential threats to stratospheric ozone. In addition to the effects of increased UV radiation on biological systems, changes in the chemical composition of the atmosphere may also produce climatic changes.

Two major environmental problems are associated with the chemistry of the troposphere: photochemical air pollution and acid precipitation. Photochemical air pollution or smog is generally limited to urban and near-urban areas. It involves the formation of chemicals such as ozone and peroxy compounds, which damage or irritate plants and animals. These chemicals are generated in air by a complex reaction scheme involving nitrogen oxides, oxygen, hydrocarbons, carbon monoxide, and sunlight. Usually the reactant chemicals are transformed into their toxic products in the vicinity of the source. In acid precipitation, sulfur and nitrogen source compounds may travel over large distances before they are transformed into strong acids that are deposited in remote rural locations. The acids may cause direct damage or they may dissolve compounds releasing toxic metals that can damage plants and wildlife.

Most chemical reactions that take place in the troposphere and stratosphere involve free radicals. These are atoms or molecules and are characterized by high reactivity, which often results from having one or more unpaired electrons. These reactions define the formation and destruction of atmospheric ozone, the oxidation of natural and anthropogenic chemicals released into the atmosphere, and the formation of acid rain. The Atmospheric Chemical Kinetics program emphasizes quantitative studies of the rates and mechanisms of the important gas phase reactions of radicals. Studies are made over a wide range of temperatures and pressures to simulate conditions in the atmosphere.

Accomplishments FY 1986

We completed two experiments in which we studied the mechanism by which sulfur dioxide (SO_2) is converted to sulfuric acid (H_2SO_4) in the atmosphere. This process has been a major source of uncertainty in modeling acid precipitation chemistry. In earlier work we showed that the odd hydrogen radicals HO and HO_2 are conserved when SO_2 is oxidized in the gas phase to SO_3 and the rate coefficient for the key reaction, $HOSO_2 + O_2$, was measured at room temperature. This work has now been extended to include the temperature dependence of the key reaction from room temperature to about 420 K. The reaction is found to have normal Arrhenius behavior. These data can be extrapolated to cover the entire range of interest for the atmosphere.

In a photoionization mass spectrometer experiment we are investigating hydrocarbon oxidation mechanisms. The initial study is on the reaction of ethyl radicals C_2H_5 with O_2, which has been studied previously in two other laboratories. The results obtained on the rate coefficient, its pressure dependence, and the yields of the two reaction channels all agree reasonably well with the previous works.

The nitrate radical NO_3 was first shown to be present in the atmosphere by the Aeronomy Laboratory's Optical Aeronomy Program. Its concentration during the daytime is negligible because it is rapidly photolyzed by sunlight. However, formation continues at night and significant concentrations are present. The NO_3 radical has been shown to be reactive toward many important atmospheric trace gases, which were thought to be inert at night because their only known reactions are with hydroxyl radicals HO which are generated by sunlight. Until recently all the kinetic data on NO_3 were obtained by indirect methods and no data were available on the temperature dependences of the reactions. We investigated the reactions of NO_3 with a series of sulfur compounds, man-made or natural. We found that SO_2 and H_2S react very slowly but that CH_3SH, CH_3SCH_3, and CH_3SSCH_3 are very reactive. It is concluded that the reactions of NO_3 radicals must be considered in the assessment of the atmospheric chemistry and lifetimes of these compounds. Our findings also indicate that a significant amount of atmospheric chemical reactions takes place at night.

The kinetics and transport properties of gaseous sodium (Na) have been studied in a fast-flow reactor with resonant fluorescence detection of Na. Sodium is deposited in the upper atmosphere by meteors. It was recently proposed that the presence of Na in the stratosphere could modify the chemistry of chlorine species that have been shown to be effective ozone destruction catalysts. The reaction of Na with N_2O was studied as a function of temperature and has been used as a kinetic source of NaO. The reactions of NaO with a series of hydrocarbons and alcohols were found to produce free sodium. NaO was also found to be reactive toward O_2 and CO_2 through association-type reactions. From these observations, it was concluded that most of the Na in the atmosphere below about 50 km will be clustered to neutral molecules in much the same way ions are clustered in this region.

We continued our investigations of the mechanism for atmospheric oxidation of hydrogen sulfide (H_2S). The objective is to determine the extent to which this compound of natural origin can contribute to the production of sulfuric acid. The first study focused on the chemistry of the HS radical. The temperature dependence of the reaction of HS with NO_2 was measured, and HSO was shown to be the product. Also, the reaction of HSO with NO_2 was studied and the product was suggested to be HSO_2, a new species in atmospheric chemistry. Although this molecule has not been directly detected in the present experiment, it has been shown to be reactive toward O_2. The discovery of this species completes the first sketch of the H_2S oxidation mechanism.

A high-resolution Fourier transform spectrometer (FTS) experiment was used to investigate the infrared spectra of several gaseous molecules, including FO, ClO, SO, CS, CF_2, and FO_2. The data are being evaluated to develop improved spectroscopic constants for the molecules. Spectra for both the ground electronic state and the first excited electronic state of SO were obtained. The FO molecule was also observed in emission from a fluorine and ozone flame.

The reaction of HO_2 radicals with ozone is very important in stratospheric and tropospheric chemistry as a mechanism that destroys ozone:

$$HO_2 + O_3 \rightarrow OH + 2O_2 \ .$$

In the atmosphere it is coupled with the reaction of OH with ozone,

$$OH + O_3 \rightarrow HO_2 + O_2 \ ,$$

and these taken together demonstrate how the odd hydrogen radicals OH and HO_2 can catalytically destroy ozone. The only direct study of the $HO_2 + O_3$ reaction was done in the Aeronomy Laboratory about 6 years ago. The difficulty in studying this reaction is that the $OH + O_3$ reaction is much faster and regenerates the HO_2 reactant. To solve this problem we use isotopically labeled HO_2 molecules and they are not regenerated by the second reaction. The rate constant was measured as a function of temperature, and the arrangement of the atoms in the reaction transition state is now known from the distribution of the isotope-labeled atoms in the reaction products.

Nitric oxide is measured in the laboratory as well as in the atmosphere by exciting laser-induced fluorescence in the γ-band. To relate the observed fluorescence signal to the concentration of NO, photophysical parameters such as the radiative lifetime and the rate of fluorescence quenching by the gases in the detection environment are needed. Experiments were carried out by exciting nitric oxide using a pulsed tunable laser. We measured the radiative lifetime of the excited NO and calculated the rate coefficients for quenching by atmospheric species N_2, O_2, H_2O, CO_2, and Ar and by H_2, Ne, CF_4, SF_6, N_2O, and NO.

The measured concentrations of O_3 in the upper stratosphere are higher than the model calculated values, suggesting that our understanding of O_3 production and removal processes is incomplete. The electronically excited nitric oxide $NO(A^2\Sigma)$ can react with O_2 to produce oxygen or nitrogen

atoms. If nitrogen atoms are produced, they react with NO to reduce the odd nitrogen concentration and thereby decrease the extent of nitrogen-catalyzed O_3 destruction. We investigated the reaction $NO(A^2\Sigma) + O_2$ by pulsed laser excitation of NO followed by resonance fluorescence detection of $O(^3P)$. We found that oxygen atoms are indeed produced, with a yield of about 40%; however, the yield of nitrogen atoms was less than 5%.

Symmetric chlorine dioxide (OClO) is believed to have an important role in the stratospheric chlorine chemistry when the concentration of total chlorine exceeds about 10 ppb. Recently, the role of OClO has taken added importance because of its hypothesized involvement in the annual springtime depression of O_3 in the Antarctic stratosphere. Long-path UV absorption measurements are under way to detect OClO in the stratosphere. To carry out such measurements, accurate UV absorption cross sections at stratospheric temperatures are needed. These cross sections are also needed to calculate the rate of photolysis of OClO in the atmosphere and for laboratory detection of OClO. We measured the absolute absorption cross sections for OClO in the wavelength range 250–480 nm at 204, 298, and 378 K, and found that some of the spectral features changed with temperature.

The rate of the reaction of carbon disulfide (CS_2) with hydroxyl radicals (HO) is enhanced by the presence of O_2. It has been proposed that the reaction proceeds through the formation of an adduct, CS_2OH, which establishes an equilibrium with the reactants, and which reacts with O_2. We directly observed the equilibrium, measured the equilibrium constant at various temperatures, calculated the heat of formation of CS_2OH from the equilibrium constant data, and deduced the rate coefficient for the reaction of CS_2OH with O_2. We initiated a search for the products of the $CS_2OH + O_2$ reaction by using a discharge flow tube coupled to a laser magnetic resonance (LMR) detector. HO_2 radicals were found to be one of the products.

On the basis of previous laboratory measurements, which indicated that OH radicals do not react rapidly with carbonyl sulfide (COS), COS is believed to be quite inert in the troposphere. However, it is possible that the rate of the reaction of OH with COS is enhanced by the presence of O_2, just as the analogous reaction of CS_2 with OH is much faster in the presence of O_2. Using pulsed photolytic production of OH in conjunction with laser-induced fluorescence detection, we investigated this reaction at high pressures. It was determined that the OH + COS reaction is not an important COS degradation pathway in Earth's troposphere, even when O_2 is present.

The reaction of OH with CO is important in determining the concentration of OH in the clean troposphere. There is a great deal of uncertainty regarding the chemical mechanism for this reaction, so we studied the reaction of CO with OD, the deuterium isotope analog of OH. We found that the rate coefficient for OD + CO increased with pressure but that the dependence is not linear. This observation, made at three different temperatures, suggests that the current theoretical understanding of the OH + CO reaction is incomplete. Since very little information was available on the photophysics of $OD(A^2\Sigma)$, which is needed to assess the sensitivity of the experimental method, we also measured the excitation spectrum, radiative lifetime of OD, and quenching rate coefficients for OD(A) with various gases.

Plans FY 1987

The chemical ionization experiment will be used to evaluate the thermochemistry of the $HOSO_2$ radical and some aspects of the atmospheric ion chemistry of SO_3. The photoionization experiment will continue work on the mechanisms of atmospheric hydrocarbon oxidation. These reactions are a central part of tropospheric chemistry since they have a role in oxidant production and they involve all major free radical families.

The study of the nighttime chemistry of NO_3 will be extended to include some hydrocarbon reactions. Certain compounds, particularly the unsaturated ones, have been shown to be reactive to-

ward nitrate radicals. The temperature dependence and products of these reactions will also be investigated.

The analysis of the H_2S oxidation mechanism will continue. The reactions and products of the HS and HSO reactions with O_3 and their temperature dependences will be studied.

The Fourier transform spectrometer will be used to examine the high-resolution spectrum of gaseous molecules. The reaction of HO_2 radicals with NO_2 will be studied to determine the relative yields of HONO and $HOONO_2$ products. The formation of significant amounts of HONO in this reaction would be an important finding because this molecule is rapidly photolyzed to produce highly reactive OH and NO radicals. The $HOONO_2$ molecule, on the other hand, has very different atmospheric effects. The high-resolution spectrum of $HOONO_2$ will be examined to find data that can be used for quantitative measurement of $HOONO_2$ in the atmosphere, by means of infrared spectroscopy. The products of the reaction of ClO radicals with HO_2 will also be examined.

Some experiments will be conducted using isotope-labeled atoms to investigate the details of atmospheric reaction mechanisms. The objective of these studies is to determine how the reactant molecules are arranged as they react. These details influence the temperature and pressure dependence of reactions and also the product branching ratios.

The reaction of electronically excited NO with O_2 will be studied further by producing NO(A) in the first vibrationally excited level. We will try to detect $N(^4S)$ directly by use of the resonance fluorescence method. We will attempt to understand this process better by determining the yield of $O(^1D)$ and NO_2.

Studies on carbon disulfide oxidation will continue. The products of the $CS_2OH + O_2$ reaction will be ascertained by using both the LMR method and the laser-induced-fluorescence method.

The photochemistry of OClO will be studied. In particular, the quantum yields for the destruction of OClO and the production of O atoms or Cl atoms will be determined.

The major source of odd-nitrogen in the stratosphere is the reaction of $O(^1D)$ with N_2O. The major loss process for N_2O in the stratosphere is photolysis in the 190–210 nm wavelength region. Experimental investigations will be carried out to assess the possibility of NO production directly from N_2O photolysis, and to measure the NO production directly from N_2O under stratospheric conditions. We will use laser-induced fluorescence detection to measure NO.

In the methane oxidation cycle a major subject of uncertainty is the chemistry of CH_3OOH. The rate coefficient for the reaction of OH with CH_3OOH, one of the CH_3OOH removal mechanisms, will be measured as a function of temperature. A pulsed Xe lamp will be used to produce OH, and pulsed-laser-induced fluorescence will be used to follow the OH concentration during the reaction. Information regarding the products of the reaction will be obtained by isotope-labeling the reactants. The quantum yield for the production of OH in the photolysis of CH_3OOH will also be measured.

Recent revisions in the absorption cross sections of O_2 in 200–220 nm region have refocused interest on O_3 photochemistry in this wavelength region. Even though O_3 photochemistry has been studied for a long time, very little is known about what happens at wavelengths below 240 nm. We will measure the quantum yields for $O(^3P)$ and $O(^1D)$ in this region by using a tunable pulsed laser for photolysis and atomic resonance fluorescence for detection of $O(^3P)$.

We have been developing methods to examine reaction products and intermediates such as CS_2OH and COOH. The newly assembled apparatus utilizes pulsed-photolytic production of free radicals and long-path UV/visible absorption technique for detection of reactant and products. A diode array spectrometer is used to measure the absorption spectra. Using this apparatus, we will ascertain products of important atmospheric reaction such as $OH + CS_2$ or CO, $ClO + ClO$ or HO_2, and $HO_2 + NO_2$ or NO.

One of the major uncertainties hindering the assessment of the role of heterogeneous chemistry in the troposphere is the lack of reliable values of the sticking coefficients γ for gas phase free radicals

and molecules on aerosol and raindrop surfaces. We are adapting a fast-flow reactor to measure sticking coefficients of radicals such as OH and HO_2 as well as molecules such as O_3, NO_2, SO_2, SO_3, H_2O_2, HNO_3, and N_2O_5 on water and ice surfaces. Development of this technique will continue; the initial efforts will be to measure the sticking coefficients for O_3.

ATMOSPHERIC DYNAMICS

The objective of the Atmospheric Dynamics Program is to further our understanding of the dynamics of the atmosphere, particularly mesoscale and small-scale dynamics of the free atmosphere. Thus, we devote a significant part of our research to the study of internal gravity waves (also called buoyancy waves) and turbulence. These mesoscale and small-scale processes are important for several reasons: (1) They are important problems in atmospheric and, more generally, geophysical fluid dynamics. (2) They are the meteorological background noise against which synoptic-scale measurements are made. (3) Gravity waves transport energy and momentum upward from sources in the lower atmosphere to sinks in the upper atmosphere. (4) Gravity waves are thought to be the source of all of the turbulence in the free atmosphere, which is the cause of most of the energy dissipation in the free atmosphere and part of the vertical mixing and transport of trace species. The study of mesoscale and small-scale processes takes advantage of the unique experimental and analytical capabilities of the group.

The observational base for the research consists largely of measurements of wind profiles obtained using the MST (Mesosphere-Stratosphere-Troposphere) radar technique. This technique measures the wind in the clear air, using very sensitive Doppler radars. Since such radars can measure wind profiles as often as every minute, about 1000 times faster than routine balloons or rockets, they are uniquely suited for studying phenomena that vary rapidly in time, such as gravity waves and turbulence.

Accomplishments FY 1986

The MST radar technique is uniquely suited for the study of gravity waves because of its rapid cadence of observation together with good height resolution. The technique measures the radial velocity versus time and radial range, leading to spectra of radial velocity versus frequency and radial wavenumber. On the other hand, theoretical model gravity wave spectra are typically expressed in terms of vertical and horizontal wavenumbers. In order to interpret MST radar spectra, we derived model radial spectra from a formalism developed for the interpretation of oceanic Doppler sonar spectra. We then compared our model with observations of the radial wavenumber in the summer mesosphere taken by the Poker Flat MST radar. Since the agreement was good, it was concluded that the observed spectra were dominated by gravity waves.

Our model has been extended to apply to gravity wave fields that are azimuthally anisotropic. Comparison between the model and observations of wavenumber spectra versus azimuth made using the MU radar in Japan shows that the field of low frequency gravity waves is highly anisotropic. This result has important implications on the generation of gravity waves and the vertical transport of horizontal momentum. In order to gain insight into the meaning of the observed spectra, we have developed a method for calculating Doppler-shifted spectra from intrinsic spectra.

In a preliminary study, we showed that the horizontal divergence of the mesoscale wind field can be estimated from dw/dz, where the w or vertical component of wind velocity was measured with the vertical antenna beam of a radar. In another preliminary study we showed that the flux of horizontal momentum due to gravity waves can be directly measured using an ST radar with five antenna beams. We found that this momentum flux is related to the jet stream.

The availability of radar profiles of C_n^2 has enabled us to develop a statistical model for the occurrence of turbulence. The model permits the calculation of profiles of C_n^2 and ϵ from measure-

ments of the background wind and temperature. The model depends upon the probability distribution functions for the unobservable, fine-structure fluctuations of vertical shear and stability, which are derived from our model of the spectrum of gravity waves in the troposphere and lower stratosphere. The turbulence model has been widely used to calculate the optical seeing in the atmosphere, for example, to assist in siting optical devices such as lasers and large telescopes. Because of this broad interest, we documented and distributed a description of its implementation, including listings of required computer programs.

Most existing middle- and high-latitude ST radars, such as our radar near Sunset, Colorado, are in or near regions of strong relief, which generate lee waves and turbulence that often vitiate the interpretation of the data. For the nation to have available a radar in a location free from this effect, the National Science Foundation has funded a 3-year project to construct and operate a state-of-the-art ST radar in very flat terrain near Urbana, Illinois. University atmospheric science groups will collaborate, both in experiments and in the analysis of data. Although this "Flatland" project was motivated by the need to measure the small vertical velocities accompanying synoptic-scale weather systems, the absence of terrain effects will also make the data uniquely valuable for studying gravity waves, turbulence, and Fresnel reflection from stable layers in the lower atmosphere. Extensive design studies were conducted using existing radar data to determine the optimum system configuration for this radar. Innovations resulting from these studies were tested with the Sunset radar.

Plans FY 1987

The research associated with the Flatland radar represents an important new direction for the program. Measurements of the vertical wind component associated with synoptic-scale systems, the horizontal divergence of the wind field, the vertical and horizontal spectrum of gravity waves, the vertical flux of horizontal momentum due to gravity waves, and the relationship of convective storms to gravity waves will benefit from the unique location of this radar in extremely flat terrain far from mountains. This research will be a cooperative university, private industry, and government effort. A special emphasis will be given to involving faculty from university departments of meteorology and atmospheric science in these experiments and their analysis.

The modification to make the Sunset radar data processing system identical to that of the new Flatland radar will be completed. The Sunset radar, with its mountain location and antenna steering capability, will remain useful for the study of mountain meteorology. The comparison of the variance and spectra of the velocity data from the Sunset radar in the mountains with that of the Flatland radar in the plains will be both unique and significant.

TROPICAL DYNAMICS AND CLIMATE

In early 1985, a growing awareness of the profound role of the tropics in influencing our global weather and climate patterns resulted in the formation within the Aeronomy Laboratory of the Tropical Dynamics and Climate/Program.

In general terms, the purpose of this newly formed program is to study, by radar techniques and ancillary data bases, the effects of small- and mesoscale dynamic processes (e.g., gravity waves, turbulence, and convection) in the tropical atmosphere on worldwide climate. Associated tasks include studies of relatively short-term climatic variations, exemplified by the recent El Niño event, which had disastrous effects over a significant portion of the globe.

The Tropical Dynamics and Climate program can contribute uniquely to such studies because of its extensive expertise in developing and using wind-profiling radar systems. Wind Profilers were originally developed by AL scientists in the early 1970s as an outgrowth of initial studies at Peru's Jicamarca Radar Observatory, itself a former AL project. The Laboratory designed the large MST

(Mesosphere-Stratosphere-Troposphere) radar at Poker Flat, Alaska, and has operated it for the past 7 years. We established a pair of more conventional Profilers in the tropical Pacific at Ponape (E. Caroline Islands) and Christmas Island (Republic of Kiribati). Similar systems have been used in temporary experimental programs in Colorado, Oklahoma, and Southern France. The Laboratory also designed and operates, with WPL, a Profiler in Platteville, Colorado, that has served as a prototype system for WPL's current program to establish a mesoscale network of similar systems throughout the Midwest. This network will provide high-resolution wind profiles to the National Weather Service.

Wind Profilers are capable of providing height profiles of the total wind vector, atmospheric waves and turbulence, spectral kinetic energy density, and gravity wave momentum flux. They can also provide a continuous measurement of the tropopause height. In addition to their ability to obtain continuous data, another major advantage of Profilers over more conventional balloon-borne systems is that Profilers measure the vertical wind. Although this parameter is considered to be a major factor in a variety of atmospheric processes, it is virtually unmeasurable on a continuous basis by any other technique. In addition, Profiler operation is continuous, relatively inexpensive, and essentially unattended.

In addition to our tropical Pacific wind Profiler program, we are also making use of the extensive rawinsonde data base that exists for some stations in the tropics, particularly in the western Pacific. This work has been mainly directed toward delineating the properties and climatology of the tropopause and the neighboring regions of the lower stratosphere and upper troposphere. The tropical tropopause is an important feature of the atmosphere, and its height and temperature have a major role in the entry of trace gases and water vapor into the stratosphere. No adequate description of tropopause properties in the tropical regions of the Earth existed prior to this study.

Accomplishments FY 1986

The Aeronomy Laboratory's Poker Flat MST radar in Alaska ceased normal operation in April 1985, following more than 6 years of almost continuous data taking. During this period, the radar produced data on atmospheric winds and related parameters in the troposphere, lower stratosphere, and mesosphere. Technological spin-offs resulted in the formation of at least one small business in Boulder's private sector. The Poker Flat radar, which was funded primarily by the National Science Foundation (NSF), was reconfigured to obtain a year-long data set of gravity-wave momentum flux (GWMF). Initial observations using the complete system in this mode began in January 1986. Earlier GWMF studies using the original system configuration, although rudimentary, demonstrated the efficacy of the technique. In addition, the 6-year data set obtained prior to the GWMF modification is being archived for the scientific community.

A recently completed study using Poker Flat data demonstrated that MST systems can also obtain useful mesospheric wind data solely by using echoes from meteor trails. This capability is being extended by the design and implementation of small, inexpensive devices that will attach to our other systems in the tropics, to measure mesospheric winds continuously. This is a joint project with the University of Colorado.

The Ponape wind Profiler, which was established in the Central Pacific in May 1984, has produced some 28 months of continuous data on vertical winds in the troposphere and lower stratosphere. We completed our analysis of the mean vertical motion, finding upward motion in the troposphere during convective episodes and weak downward motion at times of little or no convective activity. The accuracy of such long-term averaged vertical motions is sufficient for direct study of the vertical motions associated with the Hadley and Walker circulation cells that are an integral part of tropical circulation. Of comparable topical interest, the Ponape data show clear evidence of tropical "hot towers"—narrow chimneys of greatly enhanced vertical motion embedded in the large convective complexes that occur in the tropics. These hot towers exhibit vertical motions in excess of 10 m s^{-1} throughout the troposphere, and have a crucial role in vertical energy transport in the tropics.

The Ponape data also show that wind Profilers receive echoes from both the clear air and precipitation under heavy rainfall conditions. We recently completed a study of the effects of rainfall on scattering processes for Profiler applications.

A second Profiler in the tropical Pacific was established on Christmas Island with funding from Project TOGA (Tropical Oceans and Global Atmosphere). In addition to the high-time-resolution data for our analysis, 6-hourly data from the Christmas Island radar are being telemetered via GOES satellite and transferred automatically onto the Global Telecommunication System (GTS) for worldwide distribution. Long-term plots of weekly-averaged values of the wind field are published in NOAA's Climate Diagnostics Bulletin. The successful establishment of a Profiler satellite link represents a major milestone in monitoring winds from remote locations.

Preliminary tests of the Christmas Island Profilers showed that such systems are also capable of continuously monitoring ocean surface currents. This capability should provide useful information for long-term ocean studies at equatorial latitudes. For instance, a continuous 3-month record of surface currents northeast of Christmas Island shows a pronounced variability in the average westerly flow of the equatorial current.

We are in the final stages in the design and testing of an inexpensive "Boundary Layer" radar that will operate at 915 MHz, observing the region between about 100 m and 2 km altitude. This system will supplement our existing VHF system on Christmas Island to provide continuous data below the nominal 1.5-km lower-height limit of the Profiler. Current estimates of the low cost and portability of this system suggest a number of additional uses. The Boundary Layer radar represents a major new step in Profiler technology.

In addition to our activities at Ponape and Christmas Island, we continued to examine other sites to complete our proposed Tropical Pacific chain of Profilers. Discussions to install a Profiler on the campus of the University of Piura in northern Peru are at an advanced stage. Preliminary discussions with Indonesian officials indicate that the island of Biak in equatorial Indonesia is a second potential site. Radar systems for these locations can be supplied by sections of the decommissioned Poker Flat MST radar.

A study of western Pacific rawinsonde data for the intense El Niño period of 1982-1983 has shown that the potential temperature at the tropopause reached exceptionally high values, peaking in the spring of 1983. Also the zonal gradient of tropopause potential temperature, which is normally positive eastward over the five western Pacific island stations, reversed its direction and became positive westward. This occurred also during the earlier El Niño event of 1972–1973. These changes can be directly interpreted as a consequence of the movement of the center of convection from its normal location over the "maritime continent" of Indonesia to the central Pacific, and the great intensification of the convective activity. This in turn reveals the importance of advection from convective centers, accompanied by radiative warming, as a determining factor in local tropopause properties in the tropics.

A previously discovered relationship between anomalies in tropopause heights over the tropical western Pacific and anomalies in the global angular momentum of the atmosphere about the Earth's rotational axis was investigated in more detail for the 7-year period 1976–1982. Spectral analysis techniques were applied to 3-day averages of atmospheric angular momentum in 46 equal-area latitude belts and 3-day average tropopause heights from five Pacific island stations. The results showed that the overall correlation between tropopause height anomalies and angular momentum anomalies in the different latitude belts is greatest for the tropical regions, but that a highly significant coherence exists for periods in the 30–60 day range, extending to middle latitudes in the Northern Hemisphere. The 30–60 day oscillation in tropical winds is a topic of much current interest, and the existence of a similar oscillation in tropopause heights is evidence of a connection of tropical convective activity.

Plans FY 1987

Following completion of the 1-year data collection of GWMF at Poker Flat in December 1986, the station will cease operations and we will begin to disassemble and crate the system for eventual shipment to equatorial field sites.

Ongoing efforts to archive the 6-year Poker Flat data set at NCAR for the scientific community will continue throughout FY 1986 and into FY 1987. This data set will also continue to be studied within the program area to establish long-term trends in gravity wave and turbulence activity, and the seasonal characteristics of the height distribution of these parameters.

We plan to modify the Ponape Profiler at Ponape to record rainfall rate, pressure, and surface winds continuously in addition to winds aloft. Following this modification, we will operate the system in a high-height-resolution, vertically directed mode for a few months to study tropical convection processes in greater detail.

Operations at Christmas Island will continue; 6-hourly data will be supplied to TOGA scientists, and higher-time-resolution taped data will be sent weekly to Boulder (AL) for our own use. The TOGA operation is scheduled to continue for the next 7 years.

We will continue our studies of tropical convection, Hadley and Walker (vertical) circulation characteristics, and hot tower dynamics, using both Ponape and Christmas Island data. Expected outcomes of this research include an improved picture of the internal dynamics of tropical convection and the importance of hot towers, as well as a first look at measured vertical velocities of the Hadley and Walker circulation at both Ponape and Christmas Island.

We will submit to NSF a proposal covering partial funding of the installation and ongoing operation of two new Profiler sites at Piura, Peru, and (tentatively) Biak, Indonesia, and support for ongoing operations at Ponape. Initial funding will be proposed for a 4-year period. If approved, installation at Piura will begin in FY 1987.

Final testing of the Boundary Layer radar will take place in FY 1987, and an operational version of the system will be constructed. Following final testing in Boulder, this system will be installed at the Christmas Island site to operate in conjunction with the existing system.

A cooperative CU/NOAA study will examine the relationship between the anomalously strong summertime echoes observed near the mesopause (85 km) by the Poker Flat radar and the occurrence of noctilucent clouds as observed by the SME (Solar Mesosphere Explorer) satellite. Preliminary studies point to a correspondence between these two phenomena.

A joint Control Data/University of Alaska/NOAA project will examine the influence of underlying terrain on the mesoscale spectrum of atmospheric winds at tropopause altitudes. This study will use the extensive set of aircraft wind data obtained during NASA's Global Atmospheric Sampling Program. Our objective is to elucidate further the dynamical processes responsible for the observed spectrum of mesoscale atmospheric variability by determining how sensitive the spectra are to underlying terrain.

We plan to extend the analysis of the relationship between tropical tropopause properties and atmospheric angular momentum, emphasizing the seasonal and latitudinal dependence of the coherence in the frequency domain. A strong peak in the power spectrum of tropopause height variations at a period of 20–25 days will be examined in detail. The possible relationship to a known 20–30 day cycle in ocean currents and sea-surface temperatures in the eastern equatorial Pacific will be investigated.

Other pursuits using the tropical rawinsonde data base will include further development of a conceptual model of the coupling between the troposphere and the stratosphere in the tropics and an investigation of the relationship between anomalies in lower stratospheric temperatures and sea-surface temperatures. The relative importance of dynamical and radiative effects in causing this relationship is unknown.

A proposal will be submitted to NSF for funding to study the relationship between major El Niño events and quasi-periodic tree "rings" observed in the zapote (genus *Capparis*), a small tree that is

abundant in the northern Peruvian desert. Preliminary carbon-dating of one tree core indicates an age of 950 ± 30 years, a long period during which enhanced ring-widths could correspond to enhanced growth periods during El Niño events. Currently, there is no record of major El Niño events before roughly 1650 A.D.

ATMOSPHERIC WAVES AND TURBULENCE THEORY

This program is devoted to theoretical studies of turbulence, waves, and eddy transport in the atmosphere. These phenomena are basic to many areas of geophysics, including meteorology, climatology, pollution dispersal, oceanography, space physics, and aeronomy.

Wave and turbulence fluctuations are present in vast regions of the atmosphere because the natural state of the atmosphere is often locally unstable. Such fluctuations have a striking effect on transport of pollutants and were intensively observed as long as two decades ago. However, because of mathematical and conceptual difficulties, no theories of turbulence and nonlinear wave interactions were available for determining the strength of these fluctuations and how they influence pollution dispersal and meteorology. The development of such theories has become a principal concern of this program during the past decade.

Accomplishments FY 1986

This program area (1) discovered an upscale temperature cascade, in which nonlinearities cause temperature fluctuations in atmosphere and ocean to grow in size and supply a hitherto unknown major sink of energy; (2) predicted that anisotropy of dissipation greatly increases the rate at which turbulence energy is transferred from horizontal to vertical directions; (3) found a quantitative relationship between the spectral power law observed in wind spectra and the turbulence "collapse" observed in laboratory experiments; (4) derived a universal relationship between temperature fluctuations and velocity fluctuations in the atmosphere; (5) calculated the intensity of turbulence generated by gravity waves, a major source of turbulence in the free atmosphere; (6) developed a theory that will determine the combined influence of turbulence and nonlinearity on the "breaking" of gravity waves in the atmosphere; (7) calculated the Stokes drift, a downward flow in the middle atmosphere caused by gravity waves; and (8) reconciled (explained) a glaring difference between two turbulence models commonly used to predict the influence of stratification on boundary layer turbulence.

Plans FY 1987

The following studies of turbulence in the atmosphere are planned:

- Continue to develop a reliable turbulence model of the planetary boundary layer by applying contemporary methods of turbulence theory. This work is in cooperation with the Naval Environmental Prediction Research Facility (NEPRF). This year's plan is to calculate the third-order correlations that are needed to predict turbulent transport of energy and pressure from one altitude to another altitude.

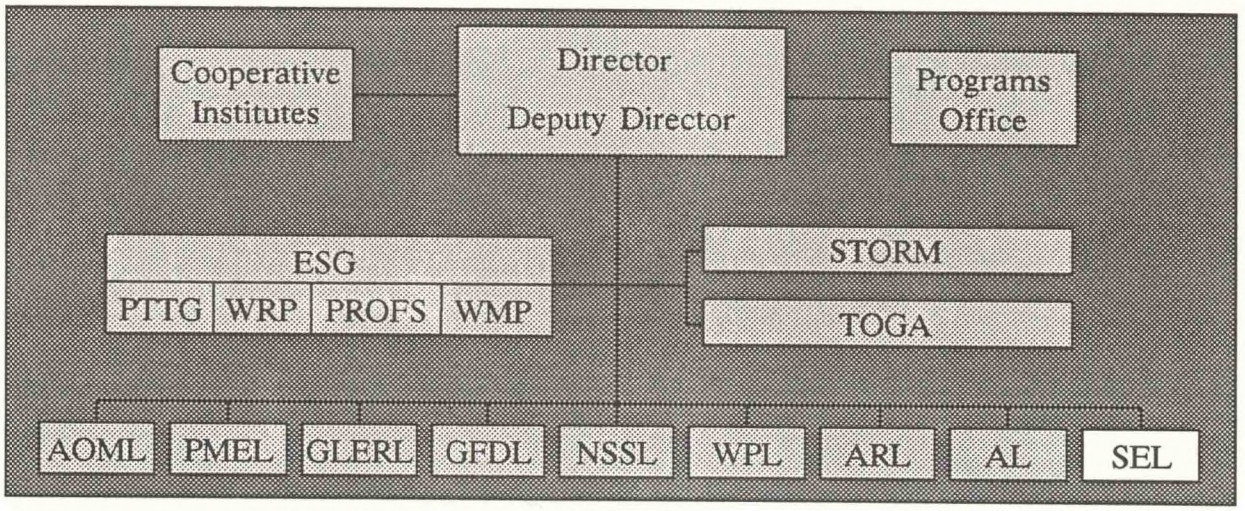
- Develop a theory to explain and predict observed ubiquitous temperature fluctuations in atmospheres and oceans. Include the influence of realistic anisotropies of velocity.

- Determine the validity of the eddy damping method widely used in turbulence modeling of the atmospheric boundary layer. Improve it, and develop alternative methods where necessary.

- Determine the atmospheric cooling caused by the upscale temperature cascade phenomenon discovered last year. This work will be in collaboration with Sidi of Service d'Aeronomie, Paris.

- Test the pressure-strain term developed last year for boundary layer modeling, by extensive comparison with numerous wind tunnel measurements of turbulence decay and by comparison with recent eddy simulations of turbulence.

Planned studies of gravity waves include (1) continuation of theoretical investigation of the spectrum and harmonics of atmospheric gravity waves, the combined influence of turbulence and nonlinearity on gravity wave breakdown and saturation in atmosphere and oceans, and the frequency and wavelength ranges for which wave saturation is caused by turbulence alone; (2) theoretical explanation for multiple breaking of gravity waves as they propagate upward; continued modeling of mass, momentum, and heat transport from 20- to 100-km altitude; (3) explanation of the unexpected variations of wave amplitudes observed with lidar by Chanin at Service d'Aeronomie, Paris; (4) explanation of the "sawtooth" wave forms observed by Ruettger at Aricebo and the end impact of such wave forms on momentum transport; (5) conceptualization of the atmospheric gravity field as a "random walk generator" and use of that concept to determine mass diffusion in the middle atmosphere; (6) continuation of major effort to determine the nonlinear properties of gravity waves from a rigorous, analytical approach.



SPACE ENVIRONMENT LABORATORY
Boulder, Colorado
Richard N. Grubb, Acting Director

The Space Environment Laboratory (SEL) is unique in ERL in providing around-the-clock service of real-time forecasts and warnings of solar and space disturbances, and at the same time, conducting research to support and improve the service activities.

The center of the nation's present solar-terrestrial services is the Space Environment Services Center (SESC) at Boulder, Colorado. This center, which is operated jointly by SEL and the U.S. Air Force Air Weather Service (AWS), provides monitoring and forecasting services to meet a wide variety of civilian, military, commercial, and Federal agency requirements. These requirements are set out in a National Plan issued by the Federal Coordinator for Meteorological Services and Supporting Research.

Activities of SEL encompass real-time collection of solar-terrestrial data, issuance of forecasts, alerts, and warnings of adverse solar-terrestrial conditions, archiving and processing of global data from satellites and observatories, and development of a better understanding of the behavior of the solar-terrestrial environment to yield significant service improvements.

SEL is composed of three Divisions: the Research Division, the Systems Support Division, and the Space Environment Services Division. The three divisions work cooperatively in providing real-time space environment services and conducting the necessary supporting research and development activities.

The accomplishments of 1986 include these highlights:

- The new SEL Data Acquisition and Display System (SELDADS II) became operational in May 1986 and will replace the SELDADS I starting at the beginning of FY 1987.
- The new color graphics workstation system, which provides for the quantitative interpretation of images acquired through the SEL Solar Imaging System (SELSIS), is being integrated into SESC operation.
- Considerable progress was made in obtaining interagency support for the installation of a Solar X-Ray Imager on the GOES-I through GOES-M satellites. When it flies in the

1990s, this new sensor will provide a major increase in our operational knowledge of the structure and potential activity of the Sun.

- Research within the Laboratory, based on operational measurements of the energy deposited in the upper atmosphere by charged particles at high latitudes, has resulted in a new picture of the way atmospheric density responds to solar activity at heights of 120 km and greater. This is expected to have significant value for predicting atmospheric drag effects on spacecraft and improving our general understanding of upper atmospheric circulation.

- A workshop on "Solar Events and Their Influence on the Interplanetary Medium" was held in September 1986. The workshop was organized by SEL and funded by NASA. The workshop was successful in fostering interactions among workers in this field, which should lead to improved understanding that can be applied to the SEL service.

- Work on a knowledge-based expert system for predicting solar flares on the basis of sunspot classification continued in collaboration with the Psychology and Computer Science Departments of the University of Colorado. The system has been integrated with a historical data base and has proved useful for forecaster training and experimental operational use. In an extended form, using more data, it is expected to be useful as an operational solar forecaster's assistant.

- The management of SEL has been modified to emphasize the interdivisional projects that have specific service-related objectives and de-emphasize the divisional boundaries. Specific responsibilities have also been assigned within the Research Division for scientific oversight of the operational sensor systems in order to assure the reliability of the data.

SPACE ENVIRONMENT SERVICES

Rapid variations in the Sun's output, including solar flares and gigantic ejections of solar mass as well as slower variations associated with the growth and decay of sunspot cycles, affect activities on the Earth. Sometimes the effects are beneficial but more often they are undesirable, harmful, and costly, and may even be health or life threatening. Activities such as these maybe affected:

- Satellite operations
  - Orbital variation and lifetime
  - Command and control anomalies
  - Ground-spacecraft communication problems

- Man-in-space
  - Radiation exposure

- Navigation system errors
  - International aviation
  - Ships and submarines

- Scientific research programs

- High-altitude polar flights
  - Radiation exposure

- High-frequency communication problems
  - Intercontinental aviation

Ships
Military
International broadcast

- Remote surveillance degradation
  Over-the-horizon radar
  Space-based optical surveillance

- Long-line network interference
  Transmission lines
  Pipelines

- Geophysical exploration
  Magnetic mapping errors
  Telluric analysis
  Archeological studies

In response to the effects on these activities, various agencies of the Federal government have initiated programs for measuring the variations, summarizing them in the form of standard indices, and predicting disturbances. Although the systems affected vary from agency to agency, the disturbances in the natural environment that produce them are the same. Therefore, the various agencies have developed a program of shared resources, from observatories and satellites that measure the environment to forecast centers that analyze the data, issue indices, and make forecasts. A description of this national program is contained in the National Plan for Space Environment Services and Supporting Research, 1983–1987 (NOAA Report FCM–P10–1983). The plan provides for joint operation of a Space Environment Services Center (SESC) by NOAA and the USAF Air Weather Service to meet the common needs for space environment services.

Accomplishments FY 1986

SPACE ENVIRONMENT SERVICES CENTER OPERATION

The Space Environment Services Center analyzes data, produces indices, and provides forecasts and data 7 days a week, 24 hours a day. The products are a standardized set analogous to the products issued by the National Weather Service. The primary mission of SESC, to maintain the continuity and reliability of service, was met in FY 1986. The mission is not simple. The relationship between disturbances on the Sun and the effects at the Earth are complex and not fully understood. Measurements of some of the most critical parameters are sparse or missing, and future progress depends on better monitoring instrumentation as well as improved understanding of the phenomena. As a step in improving its ability to deal with the forecast requirements, SEL implemented a replacement for the SESC data processing system (see SEL Data Acquisition and Display System SELDADS II below). An essential SESC task during the year was the development of a large, comprehensive set of requirements defining the operational requirements of the new system. Development was simultaneous with the forecast and analysis operations.

The services of SESC are limited to meeting the common needs of the other Federal agencies, and where they coincide, those of the public sector. The users of the service may need specialized or tailored services, which they produce themselves. On occasion, SESC provides reimbursable, tailored services to meet the needs of other agencies. For example, the operation of the NASA Solar Maximum Mission (SMM) continued in FY 1986 using space scientist expertise from SESC to develop and carry out a research-oriented observing program devoted to the improved understanding of the nature and source of solar activity such as solar flares.

In FY 1986, SESC continued in its role of World Warning Center for the International Ursigram and World Days Service (IUWDS), an organization established by the International Council of Scientific Unions (ICSU) to provide for prompt exchange of data and forecasts relative to the space environment.

The 11-year solar cycle neared its minimum in FY 1986. Solar flares and other forms of solar activity are at their lowest level of occurrence since 1976. However, the quiet levels were broken by a series of solar flares in February 1986 that produced the most intense geomagnetic storm observed since 1960. The activity produced most of the effects listed above; the number of satellite operating outages reported was particularly large. The actual occurrence of solar minimum as measured by standard indices such as the sunspot number is expected to occur in 1987.

SPACE ENVIRONMENT DATA COLLECTION

Solar Electronic Observing Network

The USAF Air Weather Service operates a network of solar optical and radio telescopes, called the Solar Observing Optical Network (SOON) and the Radio Solar Telescope Network (RSTN) at several longitudes around the world to maintain a continuous watch for solar activity and to provide many of the synoptic observations used in forecasting solar activity. The staffs of SOON and RSTN (more than 50 total) are supplied in the most part by the USAF and, by Australia, through the Learmonth Solar Observatory. The SOON and RSTN observations are provided to SESC in real time for use in the forecast operation. To maintain a liaison between the SOON/RSTN and SESC requirements, NOAA provides an experienced observer who helps staff the Learmonth Observatory. This position was maintained in FY 1986 by an officer of the NOAA Commissioned Corps who is trained and experienced in solar observing. SOON images from Holloman Solar Observatory are obtained in near-real-time at SESC (see the section on SELSIS). Other coded data from all the SOON and RSTN locations were integrated into SELDADS II.

Culgoora Observatory

The Culgoora, Australia, Solar Observatory is operated by the Australian Government to meet operational requirements for solar observations. To maintain access to the data, and keep the data responsive to U.S. needs, another NOAA Commissioned Corps Officer was stationed at Culgoora throughout FY 1986.

Kitt Peak National Observatory

Solar magnetic field and solar helium observations made at the Kitt Peak Observatory are critical for both research and real-time forecast services. NOAA, NASA, and the National Science Foundation cooperate in staffing the Vacuum Tower Telescope at Kitt Peak. This arrangement was in effect throughout FY 1986. Kitt Peak data are handled through the new SEL Solar Imaging System (see the section on SELSIS).

GOES Space Environment Monitors

Space Environment Monitors (SEMs) on the GOES satellites provide primary data for the detection and classification of solar flares and, combined with the SOON/RSTN data, for the prediction of effects at the Earth. They also provide the primary data on energetic solar particles reaching the Earth and make possible the prediction of radiation and ionospheric effects. A continuous flow of GOES SEM data is critical for the SESC operation. Such data are provided by a set of tracking systems at the Table Mountain Observatory near Boulder. The data are read out, processed, and transmitted continuously into SELDADS for use by SESC, and are made available to other users requiring the data. GOES-5 and -6 provided these data during FY 1986. The planned replacement of GOES-5, which has suffered from deteriorating data quality from its SEM, was lost when GOES-G failed to achieve orbit after launch in May. Displays of the GOES SEM data were completed as some of the earliest display data in SELDADS II in FY 1986.

NOAA/TIROS Space Environment Monitors

Space Environment Monitors on the NOAA polar-orbiting satellites provide information on energetic particle fluxes that pose a radiation hazard in the polar cap regions. In addition, they provide information on the total energy being carried into the atmosphere at high latitudes by particles precipitating from the Earth's outer magnetic field. Data coverage has been reduced since SEMs have recently been flown only on the even-numbered satellites. The most recent satellite in the series, NOAA–10, was launched on 17 September 1986.

Remote Geophysical Observing Network (RGON)

Information on the variation of the geomagnetic field at various locations over the Earth's surface is a requirement for the services operation. A part of that data base is collected using the GOES data collection platform system from a network of magnetometers and riometers operated in remote locations by universities with funding from the National Science Foundation. Accomplishments in FY 1986 included the completion of a capability for real-time stacked plots of these data for the use of the forecast operation as a part of the new SELDADS system.

Other Data

Other primary sources of geomagnetic data for the operation are obtained from the USAF and from the U.S. Geological Survey; both operate magnetometer networks and make the data available in real time. Displays of these data were completed in SELDADS II in FY 1986. The IUWDS network was also a source of additional geomagnetic data in FY 1986. Other observatories supplying data in FY 1986 for SESC operations included the Ottawa (Canada) Solar Radio Observatory, Mt. Wilson Observatory, Stanford Solar Observatory, Sacramento Peak Observatory, and the University of California at San Diego Clark Lake Observatory.

Field Site Operation

Two field sites are part of the data collection operation. The High-Latitude Monitoring Station (HLMS) at Anchorage, Alaska, is operated jointly by NOAA and the USAF to collect data from the high latitudes where many solar-terrestrial disturbances are concentrated. Data collected at HLMS are given preliminary processing and then transferred to the SELDADS at Boulder. Primary activity at HLMS in FY 1986 included development of new computer software and completion of interfaces to utilize more efficient communications systems.

Table Mountain Observatory (TMO) near Boulder receives signals from the GOES satellites and pre–processes them for relay to SELDADS. TMO is also the location of several sensor systems including a magnetometer of the U.S. Geological Survey. Operations for FY 1986 at Table Mountain gave priority to GOES data reception and magnetometer operation.

Plans FY 1987

SPACE ENVIRONMENT SERVICES CENTER OPERATION

Services operation will be maintained at present levels unless unforeseen circumstances arise. Final integration of SELDADS II into the overall operation, including revised operations procedures, will be a second objective. Third will be the participation in projects with Systems Support and Research Division staff to develop ways of expanding the analysis capabilities of SELDADS II.

SPACE ENVIRONMENT DATA COLLECTION

NOAA/TIROS

New methods of processing and displaying NOAA data have been under development. These are oriented toward providing useful information regarding the amount and location of energy input into

the upper atmosphere as measured by the NOAA Space Environment Monitor. Secondary parameters such as the thermospheric temperature can be calculated using the NOAA data as input to models. The problem from an operational viewpoint is that ways of checking the computed values are not available, and in real time, there would be no way of knowing where the model output values are valid. SESC will participate in developing methods for validation and application of these data to meet user needs.

Remote Geophysical Observing Network

Upgrading of data relay hardware to maintain the RGON links is necessary in the near future. The old hardware is becoming unreliable. Discussions are under way with the other agencies involved but plans are not final.

FIELD SITES

Plans have been made to phase out staffing at the High-Latitude Monitoring Station by mid-1990. The USAF will install a set of sensors that operate remotely with real-time data relay to meet operational needs. Early planning has begun to close the Table Mountain Observatory operation and replace it with GOES ground reception facilities at the main Department of Commerce facilities in Boulder.

RESEARCH AND DEVELOPMENT

Research and development in the most general sense are carried out in all three divisions of SEL. The Research Division carries out research in solar-terrestrial relations, with the dual objectives of improving our understanding of the effects of solar and magnetospheric disturbances on human activities, and improving our capabilities to forecast and analyze these events. Research Division staff also serve as the responsible scientists for the real-time detector systems that support the Laboratory's space environment services. Detectors include the Space Environment Monitors on NOAA's geostationary and polar-orbiting satellites, as well as ground-based monitors. The Systems Support Division provides general support to the Space Environment Services Division and to the Research Division in planning, development, and provision of instrument and data systems.

RESEARCH

Accomplishments FY 1986

MAGNETOSPHERIC PHYSICS

The objective of the Magnetospheric Physics Project is an improved understanding of the dynamic processes by which material and energy are transported from the solar wind into the magnetosphere, stored there, and eventually dissipated in the Earth's ionosphere. Both applications and research are pursued to improve the quality and utility of the Laboratory's products and services.

Data Support

Specifications of the Space Environment Monitor (SEM) magnetometer and the energetic particle sensor (EPS), which are being built for flight on the new GOES (I–M) series of satellites, were carefully reviewed. The new EPS will include a three-channel electron spectrometer, which will measure the electron energy spectrum at geostationary orbit. These new measurements will contribute to an understanding of the radiation known to contribute to the occurrence of spacecraft charging phenomena.

The group has also been actively involved in definition of the energetic particle sensor detectors for the proposed TIROS-Next series of polar orbiting satellites. These instruments, together with the GOES-Next SEM, will continue and extend the Laboratory's monitoring of the near-Earth space environment.

Some problems have occurred in the aging SEM instruments aboard the GOES–5 and –6 spacecraft, because of deterioration of the energetic particle detectors included in the monitor. Fortunately, because of the partial redundancy between the two satellites, and through systematic cross-correlation with the x-ray detector's secondary response to energetic particles, satisfactory data quality has been maintained.

An archive of space environment data obtained from the GOES satellites has been developed for use with personal computers. Five-minute averages of all SEM data channels—x-ray, magnetometer, and energetic particle—are available on two PC-compatible $5\frac{1}{4}$-inch floppy disks per month, beginning with January 1986. This data archive and distribution system was designed for maximum ease of use and transportability of data, and uses simple procedures and programs. This PC archive serves for internal data control and monitoring, and for post-event scientific analysis. The National Geophysical Data Center is discussing use of the system in its data distribution.

Data Studies

Several studies have been made using the NOAA/TIROS energetic particle data. In a cooperative study with several research groups involved with the international Middle Atmosphere Program (MAP), NOAA–8 energetic particle data were analyzed for the period of seven rocket flights in support of the MAP/WINE (Winter in Northern Europe 1983–84) campaign. The NOAA data were able to provide the energetic particle precipitation appropriate to concurrent visual auroral images obtained by the USAF DMSP satellites. Further, it was possible to establish the lack of particle precipitation during the rocket flights capable of providing energy deposition below 100 km, and consequent stratospheric warming.

In a second study, a computer code to automatically determine the minimum latitude of arrival of solar protons at the Earth (the geomagnetic cutoff latitude) was developed. This code was used in establishing a comprehensive data base of cutoff observations for some 2500 passes of the NOAA–6 satellites during solar proton event periods in 1982 and 1983. The data base includes concurrent values of a number of geomagnetic activity parameters upon which the location of the cutoff latitude is known to depend. Thus, the average global location of the cutoff latitude contours can be determined for a given magnetic disturbance condition. The cutoff contour for a given particle energy defines the size and shape of the polar region within which energetic particles are allowed access to the Earth. Such information allows better determination of the accumulated radiation exposure of orbiting satellites, or humans.

Several studies have made specific use of GOES SEM data. These include an analysis of the effects of the 3–7 February 1986 solar disturbances. A major geomagnetic storm ensued, and several episodes occurred during which the magnetopause was compressed to within geostationary orbit distance (6.6 Earth radii, Re), from its usual position at about 10 Re distance. The strength of the magnetic storm was sufficient to cause severe navigational problems to aircraft in the North Atlantic region. The disturbances also included a solar proton event, which was analyzed using data from both the GOES and NOAA satellites.

Theoretical Studies

A preliminary theoretical model of the dynamics of the Earth's radiation belt particle and energy transport processes was developed. GOES and NOAA measurements of the proton, alpha particle, and electron spectra during the solar cosmic ray event of July 1982 were used as inputs to the model. Thus, the model provides the equatorial radiation environment time history in response to such an event.

So-called Flux Transfer Events are currently considered the mechanism by which the solar wind magnetic fields interconnect with those of the magnetosphere, and transfer energy to the magnetospheric system. Theoretical studies have been conducted of the properties of flux transfer events, and their expected observational signatures. Particle signatures of such events have been found in International Sun-Earth Explorer satellite data, and further, have been found to represent a more sensitive apparent indicator of the flux transfer process than the magnetic signature through which they were identified. Further, a correlation between magnetic oscillations observed by the GOES magnetometer and the occurrence of flux transfer events indicates some potential for remote sensing of the interplanetary field by the GOES magnetometers.

Numerical simulation studies were also actively continued. In simulation studies of particle motion in a neutral point magnetic field configuration, such as that found in the geomagnetic tail, the motion is in fact found to be chaotic. The properties of processes occurring in the tail are extremely important since these process may represent (with dayside reconnection) the principal energy transfer process between the solar wind and the magnetosphere, i.e., the principal driver of geomagnetic disturbance. Further numerical studies were made of instabilities occurring between ions and electrons in the auroral zones of the Earth; such instabilities are partially responsible for the particle heating and electromagnetic noise observed in those regions.

ATMOSPHERIC-IONOSPHERIC-MAGNETOSPHERIC INTERACTIONS

The objectives of research in the Atmospheric-Magnetospheric-Ionospheric Interactions area are to understand the transfer of energy (both in the form of electrical and mechanical energy) from the magnetosphere into the upper atmosphere and to understand and characterize the various consequences that may arise in the Earth's ionosphere and upper atmosphere because of this energy input.

The observations from instruments on board the NOAA/TIROS spacecraft continue to be received, processed, and utilized for research and for the development of a method of characterizing the state of the upper atmosphere from inferences of the heat input that can be made from these observations. For the bulk of FY 1986, only data from the instruments on board NOAA-6 were available. Unfortunately, the Total Energy Detector (TED) on this spacecraft has been degrading continuously over the past 2 years and the data are now useful only after elaborate and specialized processing techniques. This impairs the usefulness of the observations as a measure of the heat budget to the upper atmosphere although selected periods of observations can still be analyzed for research purposes. The successful launch of NOAA-10 in September 1986 will rectify this situation.

The historical observations of auroral particle energy fluxes to the atmosphere (10 satellite years of data since late 1978) were used to create statistical global patterns of ionospheric-level electrical conductivities ordered as a function of the geophysical activity parameter that is derived directly from these satellite observations (i.e., the estimate of the total amount of power deposited into a single auroral hemisphere by energetic particle precipitation). The local values of conductivity were determined by using the measurements of the characteristic energy of the particle precipitation to calculate the altitude profiles of the ionization and conductivities produced by precipitation of that energy and intensity. Preliminary work was done in collaboration with researchers at the Massachusetts Institute of Technology to create statistical global patterns of ionospheric level electric fields. This project makes use of historical observations of ionospheric plasma drift velocities (from which electric fields may be derived) that have been made by the Millstone Hill Incoherent Scatter Radar facility. These radar observations have been sorted on the basis of the estimated hemispheric power input activity parameters that have been available on an almost hourly basis since late 1978 from the NOAA/TIROS observations. This analysis has yielded preliminary global patterns of electric field appropriate to each of the levels of geophysical activity defined from the particle flux data.

Once these electric field patterns are verified, each can be combined with the corresponding Pedersen conductivity pattern (suitably modified to take into account the contribution to the

ionospheric conductivity from direct solar radiation) to obtain the global pattern of Joule heat input to the upper atmosphere, in the form of either altitude-dependent or height-integrated heating rates. The Joule heat input contributes about 70% of the energy delivered to the upper atmosphere from the magnetosphere. The remaining 30% is input from direct particle precipitation, which has been characterized in the form of global patterns from previous work.

The purpose of defining these various global patterns was to specify the magnetospheric contribution to the heat budget of the upper atmosphere as a function of activity using the near-real-time observations from the NOAA satellites so that the response of the upper atmosphere and thermosphere in terms of gas densities and temperatures could be characterized. Preliminary work began, to introduce the NOAA/TIROS specification of the heat budget into a preexisting thermospheric model. These modifications were successful and the model was run to compute the behavior of the upper atmosphere in response to the NOAA/TIROS activity specifications over a period of 7 days. The results were generally satisfactory in that the temporal evolution of the exospheric temperature of the thermosphere computed from the model replicated the actual measurements of this temperature during that period. However, in order to obtain good agreement with the absolute values of the temperatures observed during this period, the electric field values used in the specification of the joule heat input needed to be increased at the higher activity levels over those provided in the Millstone Hill patterns. This highlights the requirements to (1) verify these electric field patterns and (2) verify the results of a thermospheric model that uses the NOAA/TIROS specification of the heat budget against actual observations of upper atmospheric parameters.

One important success of the effort to incorporate the NOAA/TIROS observations into a thermospheric model was that the afternoon sector of the polar atmosphere was identified as a region of particularly large energy input and atmospheric heating during geophysically active times. This feature is consistent with satellite drag observations showing maximum drag in this local time sector (indicating large atmospheric heating rates at altitudes below the satellite) but had not appeared in other dynamical or empirical models of the thermosphere.

NOAA/TIROS charged-particle observations were used together with similar observations made on board the Defense Meteorological Satellite Program (DMSP) satellites to investigate the degree of similarity of auroral precipitation structures occurring at very high latitude in opposite hemispheres. The degree of similarity (or lack thereof) places constraints on the structure of the magnetosphere at large distances from the Earth. The combination of NOAA/TIROS and DMSP satellites is particularly advantageous in that the respective satellite orbits are phased so that often one satellite of each family passes over the same latitude and local time sector simultaneously in opposite hemispheres. A classic example of a virtually identical structure occurring in both hemispheres at the same time was found; it indicates a far higher degree of order on the part of the distant magnetosphere than was thought to exist.

INTERPLANETARY PHYSICS

The objective of the Interplanetary Physics Project is to improve forecasts of the occurrence, duration, and severity of geomagnetic storms. The strategy to accomplish this goal is (1) to develop methods of monitoring disturbances as they are generated and as they travel toward the Earth, and (2) to develop, test, and implement physically based, numerical magnetohydrodynamic (MHD) models that would be driven by real-time solar observations and checked by spacecraft monitoring near Earth.

Development of Three-Dimensional Interplanetary Global Model (IGM)

A three-dimensional (3–D) time-dependent MHD model continues to be tested on a CRAY–1 computer with a simple, flat heliospheric current sheet. Formation of a magnetic "cloud" was demonstrated by the simulation of solar-flare-generated shock waves from flares in the southern solar hemisphere. A complementary model is being developed for a helmet streamer configuration at the Sun in order to develop the capability to accept inputs from solar magnetograms and soft x-ray images.

Test of $2\frac{1}{2}$-Dimensional Interplanetary Global Model

The $2\frac{1}{2}$-D IGM was successfully transferred (with vectorization capability) to the CYBER 855/205 as well as to the scientific workstation system together with achievement of additional graphics capability. A hindsight study, using only real-time data, was made of the simulated interplanetary environment that resulted from the 3–7 February 1986 solar flares. The "breadboard" IGM was partially successful in predicting most of the major shocks and parts of the temporal momentum flux variations as indicated by preliminary IMP–8 data. Other geoeffective solar wind parameters at Earth's location, such as the electric field across the magnetosphere, were also demonstrated as an important driving influence on the unexpectedly severe geomagnetic storm activity that followed these solar flares.

Study of Traveling Interplanetary Phenomena (STIP)

Plans were initiated for an interdisciplinary workshop in Huntsville, Alabama, on 12–15 May 1987. It will be sponsored by ICSU's Committee for Space Research (COSPAR), the Scientific Committee for Solar-Terrestrial Physics (SCOSTEP), and the International Astronomical Union (IAU). Collaborative efforts such as these supply many of the data needed for testing SEL's IGM codes. One important development from the collaboration has been a strategy that has implications for tracking disturbances from the Sun, through the interplanetary medium, into the magnetosphere, and down to the polar cap, auroral ionosphere, and thermosphere.

Interplanetary Scintillations (IPS) of Distant Radio Sources

Work was started to evaluate the efficiency of using the IPS radio astronomical technique for use as a real-time forecasting tool. "All-sky maps" of the interplanetary medium, prepared at the University of Cambridge (England), demonstrate that solar wind compressions and rarefactions can be observed and tracked on a daily basis by using several thousand distant radio sources (galaxies, pulsars, etc.). Collaboration started with this and other major IPS observatories (Japan, U.S.) that specialize in measurement of solar wind velocities by using a different technique. Approval of a Special Foreign Currency contract for this work with the Physical Research Laboratory in India has been obtained.

SOLAR X-RAY PHYSICS PROJECT

The objective of the Solar X-Ray Physics project is to improve medium and long-term solar activity predictions and to understand the structure and evolution of the solar corona. X-ray wavelengths are used to improve forecasts of solar disturbances that originate in that highest level of the solar atmosphere. During the past year, the activities of the project concentrated on the following.

Solar X-Ray Imager

The addition of a Solar X-Ray Imager (SXI) to the operational Space Environment Monitor on GOES is a high SEL priority. The SXI will contribute significant improvements in predictions of geomagnetic storms, solar extreme ultraviolet flux, and radiation from solar flare proton events. The operational value of the data from such an SXI was demonstrated by using 1973 data from a similar science instrument on NASA's Skylab. The 6-month Skylab mission contributed the only x-ray image information available to us. SEL plans have been formulated for the installation of three SXI telescopes on the GOES–K through GOES–M spacecraft, with first launch about 1991. Discussions are under way with other agencies to develop a cooperative program to support the imagers. Considerable progress has been made toward agreement on and planning of the design and integration of the instrument and the data systems needed for operational use.

Solar X-Ray Studies

The algorithm and program for computing solar plasma temperature and emission measure from the data available from the present GOES full disk x-ray sensor (XRS) were greatly improved. Theo-

retical emissivity data (K^{-1} Å^{-1}) were compared with those available from other sources and found to be in agreement. The transfer function for each x-ray channel, used to convert ion chamber current to x-ray flux, was found to be highly temperature dependent for temperatures less than 10^7 K, and this dependence is further affected by the defined bandpass, particularly for the short-wavelength channel. Observed maximum temperatures for selected events were compared with data from other sources to determine the effective bandpass, allowing the appropriate transfer function tables to be constructed. The methodology for analyzing the thermodynamic properties of a flaring plasma was used to investigate many flares during the high-activity period 1980–1983 and the special events of February 1986. The results of these investigations may yield astrophysically significant data regarding the constant coefficients of thermal radiation and conduction under the special conditions of a solar flare and are essential to lead to improved service applications of the data.

SOLAR PHYSICS PROJECT

The Solar Physics Project studies the nature of solar activity, its origins, and its evolution to provide the new fundamental knowledge needed for improving predictions of solar-terrestrial disturbances. The project underwent a division this year, separating x-ray studies into a new project. The remaining topics within this original project are divided between observational studies of optical solar observations and theoretical studies of the global aspects of solar phenomena.

Theory of the Solar Corona

A model of a solar prominence, based on eigenvalue solutions, was developed. The influence of vertical and horizontal magnetic fields on an isolated filament was examined. Observations of the solar corona were examined for north-south asymmetry that is predicted by a theory of quadrupole magnetic field embedded in the solar interior. Supporting evidence was found in both green-line and white-light coronal data, showing periodic asymmetry at solar minima in odd-numbered solar cycles, including the present time.

A non-self-similar theory of solar coronal transients was developed.

A basic equation for the time-dependent, force-free, electromagnetic field for the condition of cylindrical oscillations was formulated, and its solution was applied to explaining plasma resonances in the ionosphere.

Solar Mapping

Software for digitizing and displaying solar synoptic maps on advanced scientific workstations was essentially completed, including routines for making hard copies for use in publications. Data for 3 years (41 solar rotations, one map per rotation) of the 22-year data base have been entered and displayed in a time-lapse movie, and stack plots of narrow zones of latitude have been displayed in time sequence, and as individual maps, both in color and black and white.

Sufficient data are now available in digital form to permit analysis of the structure and evolution of large-scale magnetic fields and their relationships to other forms of solar activity (see next section). These data permit quantitative evaluations of growth and movement among magnetic fields. For now, simple extrapolation of such changes can be used in SESC forecasts. The current maps are being digitized each month so that the present solar situation can be viewed in the context of data for the past 3 years on workstations accessible by the SESC operations team.

The maps were seen in increasing numbers in research publications from Russia, Czechoslovakia, India, Japan, Australia, China, and the United States.

Large-Scale Solar Magnetic Fields

New displays of large-scale magnetic fields, generated from the 3 years of data now in digital form, were used in studies of flare-rich activity complexes and general patterns of evolution that may illuminate the nature of the solar cycle. Preliminary findings include the following:

- Variations occur in the average rate of solar rotation for magnetic patterns at all latitudes; there are systematic changes with the phase of the solar cycle for patterns poleward of 30° . The rotation rates of high-latitude features decelerate during the rising portion of the solar cycle, and slowly accelerate to their original value through the remainder of the 11-year solar cycle.

- The rotation rates of, and the patterns formed by, the large-scale magnetic fields are different between northern and southern solar hemispheres for the part of the 22-year data base studied thus far.

- Convergence and shear in the large-scale motions of magnetic patterns appear to be correlated with the formation of strong centers of flare and sunspot activity, although detailed statistics have not been performed. In addition, those unipolar areas of largest scale are the most stable and the least productive of emerging magnetic flux (sunspots and related flare activity). The smaller scale areas evolve more rapidly and have stronger episodes of magnetic activity. The locations of strong flux eruption, however, do not evolve into large unipolar features, dispelling the idea that the large-scale features are by-products of flux dissipated from sunspot groups.

Sunspots

A definitive description of the McIntosh sunspot classification was prepared. This includes statistics that establish the potential for this classification to be used in forecasting solar flares.

Solar Sources of Geomagnetic Activity

The merger of large-scale magnetic patterns, seen only on the NOAA solar synoptic charts, appears to account for a significant fraction of erupting filaments that are associated with coronal mass ejections. These ejections, in turn, may account for many geomagnetic storms.

Plans FY 1987

MAGNETOSPHERIC PHYSICS

- Continue oversight and evaluation of operational energetic particle and magnetometer data obtained from the GOES and NOAA monitoring instruments.

- Complete the GOES magnetometer coordinated data base, provide baseline magnetometer responses (quiet-day curves) for operational use, and begin evaluation of disturbance parameters with respect to GOES observations.

- Continue geomagnetic cutoff study, and evaluate correlation between cutoffs and NOAA measurable parameters.

- Continue to develop data processing and archiving procedures for GOES and NOAA/TIROS Space Environment Monitors.

ATMOSPHERIC-IONOSPHERIC-MAGNETOSPHERIC INTERACTIONS

- The validity of the preliminary electric field patterns that have been created will be verified. Together with this, work in using the specification of the thermospheric heat budget for NOAA/TIROS observations will be expanded and, in particular, a scheme to verify the

results obtained from exercising the model with the specification will be constructed. The plan is to use comparisons between historical satellite drag observations and the drag derived from the model results during the same time periods for which NOAA/TIROS activity parameter data are available.

- The close collaboration with personnel from SESC will be expanded with the objectives of (1) implementing the near-real-time processing of NOAA/TIROS data on SELDADS II, including the calculation of the activity parameter from the data, and (2) identifying what specific parameters characterizing the thermospheric environment are of greatest use, so that work can begin on the initial design of an operational model to produce values of these parameters from the observations.

- Routine processing of NOAA/TIROS data will continue. The archive processing software will be upgraded, particularly in the capability of identifying and excluding bad data, in preparation for the processing of NOAA-10 data as they become available.

INTERPLANETARY PHYSICS

Tests of $2\frac{1}{2}$-Dimensional Interplanetary Global Model

- The test of the $2\frac{1}{2}$-D IGM will be continued in the context of the major February 1986 solar flares and geomagnetic storm activity. The existing simulation will be extended to take into account several solar coronal holes whose high speed solar wind streams were inferred from preliminary IMP-8 data. This sensitivity study will then be compared with the existing one that considered only the solar flares. Graphics displays of the model output on the scientific workstation will be extended. Candidates for other tests of the IGM will also be considered. Extension of the $2\frac{1}{2}$-D IGM to the base of the corona in both the ecliptic and meridional planes will be started.

Development of Three-Dimensional Interplanetary Global Model

- The 3-D IGM will be transferred from the CRAY-1 to the CYBER 855/205 computer, and the code will be tested for a sinusoidal heliospheric current sheet that more nearly represents active Sun conditions. A pilot study to extend the 3-D IGM to the coronal base will also be started in collaboration with CIRES associates and contractors.

Study of Traveling Interplanetary Phenomena (STIP)

- A proposal will be made to the National Science Foundation in collaboration with a number of academic scientists to sponsor one or more workshops on modeling disturbances in their complete path from the Sun through to their effects in the polar cap, auroral regions, ionosphere, and thermosphere. An STIP Symposium on Physical Interpretations of Solar/Interplanetary and Cometary Intervals will also be held with SEL leadership and participation in Huntsville, Alabama.

Interplanetary Scintillation (IPS) of Distant Radio Sources

- A joint IPS study will combine Cambridge "all-sky-maps" with Toyokawa's solar wind velocity measurements that followed a combined eruptive prominence and coronal hole event on the solar disk in September 1980. SEL's 3-D IGM data with an algorithm that produces all-sky maps that are equivalent to those produced directly from the IPS observations.

- SEL's 3–D IGM data will be combined with an algorithm that produces all-sky maps that are equivalent to those produced directly from the IPS observations. The same algorithm, with some modification, will use another (coronal) link in the IGM approach to produce images that are equivalent to those produced directly from coronographs that reveal coronal mass ejections.

SOLAR X-RAY PHYSICS

Solar X-Ray Imager

- Facilitate the signing of the Memorandum of Understanding for interagency implementation of the SXI. Provide consultations and backgrounds for appropriate groups in the executive and legislative branches.
- Provide for technical liaison with GOES-Next contractor and subcontractor groups on the SXI, with SXI project groups at the other sponsoring agencies, and with potential data user groups.
- Begin to provide for future SXI research support. Develop a prioritization of research tasks in support of services by the SXI. Outline necessary calibrations, operating modes, and algorithms for rapid utilization of SXI data. Assess future science goals.

Solar X-Ray Studies

- Investigate the thermal properties of solar flares using wide-band, soft x-ray flux measurements. Seek physical parameters that allow improved evaluation of the geophysical consequences of the flares.
- Support the operational GOES x-ray sensor and its data handling system more closely to improve the quality of data with respect to calibration, noise, and accuracy.
- Oversee the development of the GOES solar x-ray sensor for satellites I–M, to ensure maximum performance of the new design that will be used on these three-axis stabilized spacecraft.

SOLAR PHYSICS

- Develop a program for translating bit-maps of solar maps into digital arrays that can be stored on magnetic tape and shared with scientists having different types of computers. These digital data are needed for fast, detailed analyses of the distribution and evolution of large-scale solar magnetic fields, for comparisons with models of the solar cycle. The digital arrays can be used to generate data displays of identical format to data from other observational systems.

DEVELOPMENT

Accomplishments FY 1986

SPACE ENVIRONMENT DATA SYSTEMS

SEL Data Acquisition and Display System

The SEL Data Acquisition and Display System (SELDADS) is a large, distributed processing system that supports the operation of the SESC. It collects the real-time data into data bases, drives

displays for the use of the SESC staff, is used in producing the standard forecasts and indices, acts as a communications interface, and provides access to the data base for dial-up users. The standard period of retention in the data base is 32 days, after which the data are archived in the National Geophysical Data Center (NGDC) in NOAA's National Environmental Satellite, Data, and Information Service. The original SELDADS I was initially conceived in the early 1970s and grew intermittently as pieces of hardware became available. Finally, SELDADS I could not accommodate and display all the real-time data, and system reliability had deteriorated. SELDADS I has been replaced by a new system, designated SELDADS II, over the past 2 years. SELDADS II hardware was delivered in 1984 and a phased program of implementing software has been in process since that time. The application software, the portion of the system that serves the staff of the SESC, was developed on the basis of user requirements after extensive analysis of the steps that occur in the solar-terrestrial analysis and forecast process. Software was developed by members of a SELDADS II Implementation Project, composed of personnel from the SEL Services and Systems Support Divisions, and assisted by staff of the SEL Research Division. Data ingest, data base operation, displays, listings, product generation, communication interfaces, and access for external users were completed in FY 1986 to the level that SELDADS I was turned off and operation shifted completely to the new system.

SEL Solar Imaging System

The SEL Solar Imaging System (SELSIS) is a new digital image handling system developed by the staff of the SEL Systems Support Division, on the basis of requirements for SESC operations. The system is capable of collecting images from suitably equipped solar observatories, storing the images in an on-line system, processing to correct problems of orientation and sizing of the images, and providing CRT displays and hard copy to the SESC forecasters. The system operated in a developmental mode in FY 1986 and provided images but no processing to both the SESC forecaster and the Solar Maximum Mission Operation Center at the Goddard Space Flight Center. Observatories connected into the system include the USAF Holloman Solar Observatory and the Kitt Peak Observatory.

A major effort has been the development of the more competent new central display and processing system for SESC. This is based on a commercial color workstation computer and provides for image scaling, rotation, and contouring capability, as well as a laser printer system for hard copies. The system, with this phase 1 capability, will be installed in SESC early in FY 1987. Phase 2 software development will encompass more advanced image processing and quantitative interpretation capabilities.

GEOMAGNETIC FORECAST DEVELOPMENT

Approximately two-thirds of the SESC users are primarily concerned with disturbances in the Earth's geomagnetic field. Providing data and forecasts to serve these users is complicated by problems of understanding the complexities of the Sun-Earth connection and in specifying the nature of a geomagnetic disturbance to users in various areas since the characteristics vary from region to region over the surface of the Earth. An intensive effort to improve the geomagnetic services has been developing over the past 2–3 years. In FY 1986, a focus of the effort was a workshop on solar effects and their influence on the interplanetary medium, funded by NASA and SEL. The workshop brought together members of the international research community with the goal of establishing the current state of knowledge in linking solar activity to disturbances in the interplanetary medium and identifying areas of research to improve the level of understanding. A program of recommended work was laid out at the workshop.

Another prospective source of improvement to forecasts is the provision of climatological information on geomagnetic activity to duty forecasters. Until now, numerical guidance has not been routinely available to forecasters. The statistical analysis to establish a base for climatological forecasts was completed in FY 1986 for future implementation in SELDADS II.

SOLAR FLARE FORECASTING AND ANALYSIS DEVELOPMENT

Development activities aimed at improving solar flare forecasts included work on developing an index to measure magnetic field "shear," caused by the relative motion of sunspots or other strong magnetic fields in the surface of the Sun, and believed to be the means of storing energy for solar flares. The work is being done using the solar magnetograph at NASA's Marshall Space Flight Center and in cooperation with the U.S. Air Force.

Part of the development of requirements for SELDADS II included a capability for receiving coded characteristics of solar active regions from the U.S. Air Force SOON and using them in numerical models for forecaster guidance. These are being held for future implementation in SELDADS II.

OPERATIONAL SATELLITE INSTRUMENTATION PROJECT

Data from operational Space Environment Monitors (SEM), which are carried on the NOAA/TIROS and GOES spacecraft, are essential to the operation of SESC. The provision of instruments to replacement spacecraft and the development of new or improvement of existing instruments for spacecraft is, therefore, a very important supporting activity.

Instruments are normally produced by contractors (or subcontractors) to NASA, which acts in turn to supply NOAA with the entire operational satellite. SEL sets the requirements for the SEM system and assists with the technical supervision of the instrument contractor. When necessary, SEL also repairs and recalibrates instruments that are awaiting flight.

During FY 1986 the Medium Energy Proton and Electron Detector (MEPED), which was launched on NOAA-10 in September, was checked and requalified before delivery to the spacecraft contractor. The performance of SEM on NOAA-10 will be checked out after the instrument is turned on in FY 1987.

GOES-H and its SEM were lost, owing to a Delta launch vehicle failure. The existing SEM systems on GOES-5 and -6 are now showing some degradation due to radiation damage to the solid state detectors in the Energetic Particle Sensor (EPS). Steps were taken to correct the data and to minimize the effects of the damage by maintaining detector bias during eclipse periods. The new SEM, which will be launched on GOES-I later in FY 1987, will provide a new system to replace that on GOES-5, which has been in orbit for 5 years.

In February 1986 NASA formally asked the Laboratory to manage the procurement of the three SEM systems, which will be required for the proposed NOAA-K,-L, and -M follow-on spacecraft. A Technical Advisory Committee has been set up and the technical specifications completed. The Source Evaluation Board for the procurement has been appointed and is expected to meet and finalize the Request for Proposals early in FY 1987.

The GOES-Next program (satellites I-M)has been supported by taking part in the Preliminary Design Reviews for the new SEM instruments needed for the three-axis stabilized spacecraft. The continuing effort to provide an operational Solar X-Ray Imager as part of the new GOES series was supported with analysis of the proposals for the imager from potential instrument contractors, and the spacecraft contractor's accommodation studies.

Ongoing data quality control is essential if the data from the operational sensors are to be reliable for operational use. Under the SELDADS I system, detailed quality control and evaluations could only be done on the off-line CYBER system, because of the limitations on the real time processing. With SELDADS II this limitation no longer exists in such an extreme form and a new automated data quality review system is being implemented to run in near-real time on SELDADS II. This system abstracts instrument calibration data and spacecraft housekeeping into a separate engineering file, which will be analyzed daily. Summary outputs will provide data on any apparent changes in instrument performance or significant trends. The system is now in experimental operation on SELDADS II.

DEVELOPMENT OF EXPERT SYSTEMS—THEO

Knowledge-based "expert systems" attempt to capture on computer the knowledge of a human expert in a limited domain and make this knowledge available to a user with less experience. Such systems could be valuable as an assistant to a forecaster or for training purposes. SEL has continued to work cooperatively with the Computer Sciences and Psychology Department of the University of Colorado in Boulder to develop the expert system for sunspot classification and solar flare forecasting, which was started as a pilot project in FY 1985. This system is known as THEO after Theophrastus, an ancient Greek scholar who is credited with having been the first to observe sunspots. Within SEL this work is a joint effort between the Solar Physics project, and the Systems Support and Services Divisions.

THEO has been integrated with a data base so that previous history is always available to the forecaster, and the structure of the program has been improved. Improvements to the user interface and the ability of the system to explain its logic and data base make the system easy for novice forecasters to use. A default version of the system was developed to make it possible to produce a conservative forecast with incomplete data direct from the computer database without requiring interaction from a user. This enables THEO to run very quickly, giving rapid advice to a forecaster in circumstances when operational activity prevents detailed analysis. The default version produced a complete forecast in less than 5 minutes even on a day with 15 groups of sunspots and many large flares. Work is now under way to extend the verification testing and better understand the differences between its performance and the human expert, which it emulates. A start has been made on defining rules for the use of data on the active region structure in addition to the white light sunspot structure.

The developmental system has been made available within SESC on a workstation computer and has been used for training and demonstration purposes. In principle it is available for experimental operational use, although solar activity has been so low for most of the period that its application has been very limited.

SEL SCIENTIFIC WORKSTATION SYSTEM

With the development of high-performance 32-bit microprocessors and high-resolution graphics systems, it is now feasible to consider a workstation at a scientist's desk, to be the single point of contact for all computational and graphical display needs. The local computational capability provides rapid source code editing and debugging. Networking to other workstations and to the DOC mainframe scientific computer system provides the power for major computations and the capability to return the results for graphical display and manipulation.

During FY 1986 the SEL network of workstations was expanded by the delivery of five monochrome workstations, which brought the total number of stations in the network to nine. Seven of these have computational capabilities approximately equal to a VAX 11/780. Network connections were installed to the DOC CYBER mainframe system and to the operational SELDADS system.

The graphics support available to scientific users was enhanced by porting the SEL DPLOT device independent graphics software to the workstation system. This makes it much easier for a scientific programmer working in FORTRAN 77 to use the power of the workstation graphics and makes it possible to move graphics applications between the CYBER mainframe, the operational MV1000 SELDADS system, and the workstations, while choosing from a variety of output devices. Applications developed using this package ranged from graphical output of interplanetary disturbance models to verification of SESC forecast performance and display of operational satellite data. Use of the workstations was also applied to development of the Knowledge-Based Expert Systems and to magnetospheric modeling.

A commercial software package and laser printer system was added to the workstation system to provide publication quality text and graphics. A DPLOT driver was developed. The complete system is now employed in SEL for scientific papers, for which it provides mathematical equation support and

also for presentation material and the SESC weekly publication. It is also being used to produce this edition of ERL Programs and Plans.

Plans FY 1987

SPACE ENVIRONMENT DATA SYSTEMS

SEL Data Acquisition and Display System (SELDADS)

Now that SELDADS II is operational, attention will now be concentrated on enhancing its capabilities beyond those of SELDADS I. The priorities are (1) completion of some operational tools not included in the original system (processing routines that reduce the time that the forecasting staff must spend in massaging data or other tasks that the machine can assume); (2) display of all real-time data available in the data base, a task that was beyond the capability of SELDADS I; and (3) development of new analysis capabilities such as the ones for geomagnetic and solar forecasting that provide numerical guidance in some form.

SEL Solar Imaging System (SELSIS)

SELSIS implementation will continue with the following:

- Procurement and installation of additional observatory processors.
- Installation of the SESC processor and integration of the image processing into the daily operation.
- Completion of a hard copy capability and elimination of dark-room processing of local images.

The new color workstation will be installed in SESC, and staff training and operational integration will be completed. The software for phase 2, which includes feature recognition, viewpoint translation, and various multiple data presentations will be developed. If budgeting constraints permit, observatory processors will be installed at the USAF solar observatory at Ramey AFB in Puerto Rico, Big Bear Observatory in California, and Sacramento Peak Observatory to provide additional data sources.

GEOMAGNETIC FORECAST DEVELOPMENT

The emphasis in geomagnetic forecast development will be to develop the system to provide geomagnetic forecasts in the form of probability of occurrence of six levels of activity in place of the present forecast of a single expected index with no confidence level indicated for that forecast. Development of numerical guidance for forecaster use, including climatology, is also planned.

SOLAR FLARE FORECASTING AND ANALYSIS DEVELOPMENT

A method of providing numerical guidance for solar flare forecasts was developed in a large study completed previously in cooperation with the Air Force Geophysical Laboratories and the National Bureau of Standards. Implementation of the model in SELDADS II began in FY 1986. The observatories in the USAF SOON system will compile a set of parameters for each active region on the Sun. The parameters have been tested and shown to be most significant in predicting solar flares. Input from the SOON will be provided to SESC on a regular schedule several times per day. It will be used to drive a numerical model that will provide continuous guidance to the duty forecaster. Other work will include development of a test for measuring a solar-active region shear index that may be useful in flare predictions. The THEO expert system for flare forecasting will be implemented as a forecaster training method in SESC.

OPERATIONAL SATELLITE INSTRUMENTATION

The launch and SEM instrument check-out for GOES–I will be supported. NOAA–G post-launch SEM check-out will be carried out.

The GOES contractor and instrument subcontractors for satellites I–M will be reviewed as required to ensure future satisfactory SEM systems.

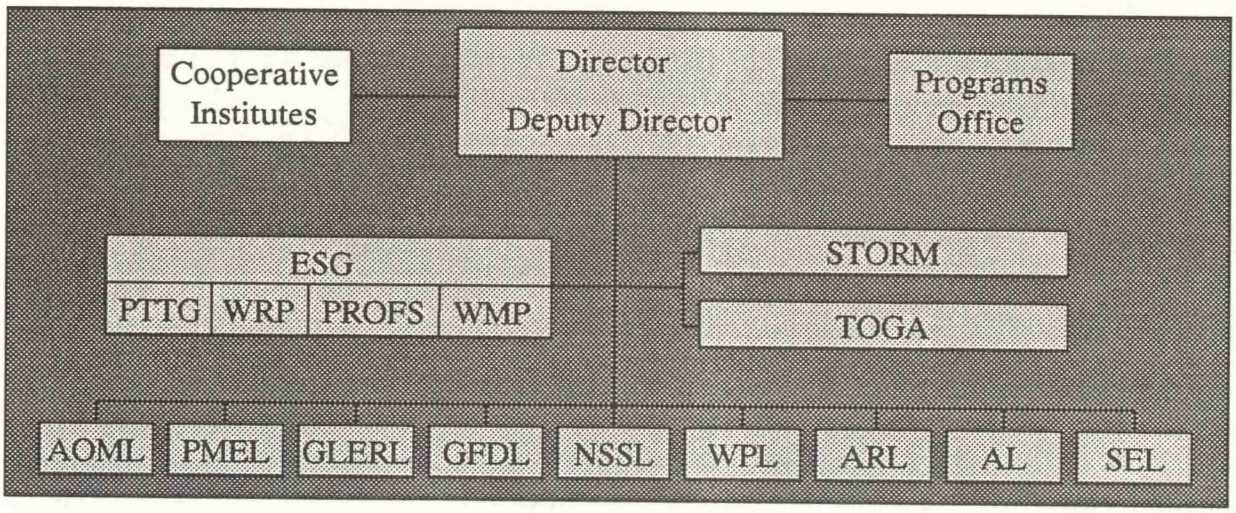
The procurement process for the TIROS–K, –L and –M SEM subsystems will be continued. If the spacecraft program continues on schedule and the necessary approvals are forthcoming a contractor will be selected and under contract to build the subsystems by mid-FY 1987.

DEVELOPMENT OF EXPERT SYSTEMS--THEO

- Run second test period to refine evaluation of ability of THEO to emulate expert, to determine what factors enable an expert to excel THEO at certain times, to evaluate influence of data quality on performance, and to enlarge the data base for more meaningful comparison between THEO and official NOAA forecasts.
- Complete insertion of explanatory texts within THEO that enhance its ability to train novice forecasters.
- Complete documentation and publication of description and tests of THEO.
- Begin adding other knowledge bases, such as chromospheric and magnetic-field solar observations, to make THEO more like the NOAA forecast operations.

SCIENTIFIC WORKSTATION SYSTEM

If budgeting constraints permit, the system will be expanded to make workstations more readily available to a greater number of research and development staff.



CIRES

The Cooperative Institute for Research in Environmental Sciences (CIRES) is jointly sponsored by the University of Colorado and NOAA and receives roughly equivalent support from other public and private sources. CIRES Fellows have academic affiliations with eight departments at the University of Colorado: Chemistry, Chemical Engineering, Physics, Geography, Geological Sciences, Electrical Engineering, Mechanical Engineering, and Astrogeophysical, Planetary and Atmospheric Sciences. Current research in CIRES is in four broad areas: Environmental Chemistry, Atmospheric Dynamics, Climate Dynamics, and Solid Earth Geophysics.

ENVIRONMENTAL CHEMISTRY

The areas of research include environmental measurements and analysis, reaction kinetics, biochemistry, surface science, and analytical instrumentation. Recent studies are applicable to such diverse subjects as acid rain, air and water pollution associated with energy development, climate change resulting from carbon dioxide emissions from fossil fuel burning and other pollutants, stratospheric ozone depletion, improvements in catalyst technology, photochemical oxidant formation in the troposphere, biogenic emissions of important trace gases to the atmosphere, earthquake hazard evaluation based on gaseous emissions from the ground, protection of crops against frost, marine measurements of chlorofluoromethanes as transient tracers of ocean circulation and global uptake of pollutants by the sea, and evaluation of the atmospheric consequences of nuclear warfare.

Accomplishments FY 1986

CIRES research in environmental chemistry contributed to important NOAA programs in acid rain, radiatively important trace species, and global atmospheric chemistry. These contributions include laboratory studies of basic chemical and biochemical processes, development of measuring techniques, and field measurements.

LABORATORY STUDIES

Laboratory studies in CIRES have focused on elucidating the basic processes that determine chemical and biochemical transformations. These studies provide input data to the numerical models

that are used to simulate atmospheric composition, to uncover reaction mechanisms that form the basis for detector development, and to understand the factors that regulate chemical, biochemical, and geochemical cycling.

Gas Phase Chemistry

The reaction

$$ClO + BrO \rightarrow Cl + Br + O_2$$

has been proposed as a possible explanation of the recently discovered Antarctic ozone "hole." A depletion of the order of 50% in the column abundance of stratospheric ozone has been found to develop over the Antarctic continent in the spring of each year. The extent of ozone depletion has grown steadily since the mid-1970s. The ClO+BrO reaction could catalyze ozone depletion once ClO and BrO radicals are formed by photolysis processes, i.e., upon the return of sunlight following the polar night. Because of the potential importance of this reaction in explaining the depletion, CIRES researchers measured its rate constant and product distribution as a function of temperature. The rate constant was found to be quite fast ($\sim 1 \times 10^{-11}$ cm^{-3} molec^{-1} s^{-1}). It is possible, therefore, that this reaction has contributed to the rapid rate of ozone depletion observed over Antarctica.

A variety of trace compounds, natural as well as anthropogenic, can contribute to atmospheric chemistry. The molecule S_2 is known to be sporadically emitted to the atmosphere by volcanic eruptions, yet nothing has been known about its reactions in the atmosphere. For this reason, reactions of S_2 with the atmospheric species O, O_2, O_3, N_2O, NO, and NO_2 were studied using the fast-flow technique with mass spectrometry for detection. Of these species, it was found that only oxygen has a fast reaction, and its rate constant was measured. From this work, it was concluded that, in the stratosphere at least, the most important sink for S_2 is oxidation to SO by oxygen atoms.

Surface Chemistry

In addition to gas phase chemistry, an active program is under way, aimed at understanding the mechanisms responsible for chemical conversion on surfaces. These mechanisms form the basis for new analytical techniques being developed at ERL and at the University of Colorado that rely on the catalytic surface conversion of compounds-of-interest to compounds that can be detected more specifically and sensitively. In particular, the conversion of NO_2 to NO on a metal surface in the presence of a suitable reducing agent is of interest. To better elucidate the mechanisms involved in the reactions of NO_2 at metal surfaces a program to study the details of these interactions was undertaken.

The initial work focused on the interaction of NO_2 with a platinum(111) single crystal surface, which serves as a well-defined model catalyst. The results suggest that the catalytic reduction of NO_2 will be very sensitive to the catalyst temperature, the concentration of O_2 in the entering gas, and the catalyst's thermal and gas history.

Biochemistry

Just as atmospheric composition can affect the biosphere, so too can biochemical processing influence atmospheric composition. For example, the natural emissions of sulfur-containing biogenic compounds provide the irreducible minimum background for sulfuric acid, which is the principal acid deposited in the eastern United States. An understanding of the natural component of this sulfate deposition requires an understanding of the biological processes responsible for the natural sulfur emissions.

To understand the mechanisms that generate the sulfur compounds, and therefore the specific factors that determine the emissions, CIRES and the Aeronomy Laboratory developed laboratory-scale experiments that emulate these natural processes under controlled conditions. These studies used an environmental chamber technique, with which it was possible to study the effects of environmental variables (e.g., light intensity, temperature, carbon dioxide levels) on such emissions. Fluxes of

dimethylsulfide, hydrogen sulfide, and methanethiol from corn, alfalfa, and wheat were observed to increase by as much as a factor of 4 as illumination varied from zero to mean summer daylight levels. By varying the CO_2 content of the chamber flush gas, it was shown that the observed sulfur fluxes are not the result of CO_2 depletion. Techniques were developed that allow the emission or uptake of sulfur gases from the aerial parts of plants to be distinguished from emission or uptake by the soil. Using these techniques, we demonstrated the light-dependent uptake of COS by growing vegetation, and improved interpretations of data obtained in previous field studies of sulfur fluxes from soils and vegetation.

MEASUREMENT TECHNIQUE DEVELOPMENT

The design of successful field measurements relies on the development of instruments capable of detecting trace quantities of chemically active compounds free of artifact and interference. The development of new instrumentation has been actively pursued in CIRES during the past year.

A "redox chemiluminescence detector" was developed. This detector is a selective and sensitive device for use with chromatographic systems for the analysis of environmentally significant compounds. Developmental research is focused on understanding the chemistry of the catalyzed reactions, factors determining selectivity, the oxidation chemistry of organic substrates, and problems associated with application to liquid chromatography.

The selectivity of the redox detector depends on several factors including the metal used, substrate composition, and operating temperature. For example, when palladium is the catalyst, the detector is generally sensitive to alkanes and alkenes, but when a gold catalyst is used, the more abundant and less interesting alkanes are not detected. Such discrimination is important in analysis of trace-level components that are otherwise difficult to detect in the presence of the ubiquitous alkanes.

The redox detector has been applied to liquid chromatography. Liquid-phase oxidations with aqueous nitric acid also produce NO upon reaction with alcohols, phenols, and sugars. These results are important for the development of detectors that can selectively detect non-volatile oxygenates from extracts of atmospheric particulate matter. Another new analytical technique, developed by CIRES scientists, couples capillary gas and supercritical fluid chromatography to supersonic jet spectroscopy and uses laser-induced fluorescence detection to increase the sensitivity and selectivity of fluorescence detection of chromatographic effluents. A major contributing factor to the success of this method was the development of a sheath flow nozzle, which interfaces capillary chromatography to the "jet" expansion that cools the sample. This interface uses a gas-focusing effect to achieve excellent sensitivity (detection limits of tens of picograms) while retaining chromatographic resolution. The method has been applied to the detection of hazardous pollutants, such as polycyclic aromatic hydrocarbons, in complex samples.

FIELD MEASUREMENTS

CIRES scientists have contributed significantly to major field studies carried out by ERL (and described elsewhere). However, one major study was coordinated through CIRES. The Arctic Gas and Aerosol Sampling Program (AGASP) is a cooperative research program designed to determine the distribution, transport, chemistry, aerosol physics, and radiative effects of the polar air pollution phenomenon known as Arctic haze. Conceived, organized, and directed by NOAA, the program involves participants from the United States, Canada, Norway, Sweden, Federal Republic of Germany, and Denmark, and covers two intensive field study periods in March-April 1983 and 1986. The core field research program consists of airborne measurements tied to similar baseline station measurements at Barrow, AK; Alert, N.W.T., and Ny Alesund, Spitzbergen. In the just-completed second field activity period (AGASP-II), the heavily instrumented NOAA P-3 flew three 10-h missions from the GMCC Barrow baseline station, then flew to Thule, Greenland, where joint flights were conducted over the Canadian baseline station at Alert with the University of Washington and the Atmospheric Environment Services (Canada) aircraft. Overhead and upwind of the Barrow station, profiles of gases and

aerosols were obtained from 30 ft above the surface into the stratosphere. Over Alert, four similar profiles were completed, two in conjunction with the Canadian aircraft. The other two were preceded by fly-overs of the University of Washington aircraft, which mapped the haze layers from 18,000 ft to the surface, prior to the NOAA P-3 profiles.

On the first flight in the Alaska portion of the program, the NOAA P-3 found and characterized a 50-mile-wide transport zone of pollution more dense than pollution observed in AGASP-I. This anthropogenic pollution contained up to 990 ng m^{-3} of soot carbon and produced optical depths of 0.7 to 0.8. This same haze subsequently passed over the Barrow baseline station where it was extensively characterized. For the next 2 days, it moved south over Fairbanks where the P-3 flew in it and the University of Alaska Poker Flats Observatory collected surface samples. The haze subsequently moved south over Anchorage and out to sea. This is the first well-documented study of Arctic haze moving completely across Alaska.

On other flights, the NOAA P-3 penetrated the stratosphere over Alaska where heavy loadings of fresh volcanic debris were collected. These materials bear the same mineral signature as the debris from Mount St. Augustine, which erupted the first week of the AGASP-II field program.

In addition to the AGASP program, other studies involving atmospheric aerosol measurements are under way in CIRES. The sources, transport, and chemical transformations of atmospheric particulate matter were investigated using a new analytical technique that permits hourly time resolution of the volatile organic composition of samples that are collected on quartz fiber filters. Data on 55 meteorological and chemical variables for 138 samples collected in Boulder, Colorado, were subjected to statistical factor analysis, which revealed characteristic signatures for photochemical activity, biological sources, and motor vehicle sources. The organic compounds identified in the samples include biogenic terpenoids, alkanes from both vehicular and biological sources, and aldehydes, ketones, carboxylic acids, lactones, and furans from photochemical transformations and other sources.

OTHER ERL PROGRAMS

In addition to the research efforts that are being carried out in CIRES laboratories, CIRES research associates and assistants are collaborating with ERL scientists on a variety of programs, including the measurement of the global budget of CO_2, methane, and several fluorocarbon compounds; studies of stratospheric ozone depletion; measurement of natural emissions that contribute to atmospheric acidity and alkalinity; investigation of processes involved in acid deposition, the tropospheric/stratospheric exchange processes, and kinetics of tropospheric and stratospheric reactions.

Plans FY 1987

The programs described above are ongoing and will continue. Other program areas will contribute important new capabilities to CIRES basic research.

Studies of NO_2 on the platinum surface will be extended to gold surfaces. To understand the catalytic reaction mechanisms for NO_2 in converter tubes used for atmospheric measurements, two studies will be undertaken. Initially, the spectroscopic measurements similar to those that were carried out for platinum surfaces will be carried out for gold. This will give information on the nature and energetics of elementary processes that are occurring in the gold converter tubes (e.g., adsorption, desorption, and reaction). In addition, steady-state and transient reaction kinetic measurements will be made on gold surfaces under conditions where there are no diffusion limitations on the observed catalytic rate. These measurements will explore the reaction mechanism under interesting conditions and characterize the rate in terms of the apparent activation energy and the kinetic order of the pressure dependence of the rate on the reactants and products. Correlation of these kinetic data with the spectroscopic data should allow for a good understanding of the rate-limiting step of the reaction and for possibilities of increasing the rate or selectivity of the catalytic reduction of NO_y.

NO_x ($NO+NO_2$) plays a key role in atmospheric formation of ozone and is the precursor to nitric acid. It is now recognized that NO_x emissions from the soil constitute one of the important natural sources of NO_x. The environmental chamber studies that have been applied successfully to the study of the factors that control sulfur emission and/or uptake by soils and vegetation will be used to investigate the factors that control NO_x emission and uptake by soil and vegetation.

Efforts will continue to adapt redox chemiluminescence detectors for use with liquid chromatographic systems. In addition, two new techniques for studying particulate organic compounds will be investigated. Current methods are generally limited to compounds that are either volatile or extractable with organic solvents. Tandem mass spectrometry with fast atom bombardment ionization of organic particulate matter may offer a means to detect and characterize less volatile compounds without a significant amount of sample preparation. Another potentially useful method for studying nonvolatile organic compounds is by supercritical fluid extraction of particulates. This should be a more efficient way to prepare samples than the currently used solvent extraction procedures. When combined with supercritical fluid chromatography, this method could extend the range of particulate studies to large organic compounds that are currently difficult to isolate and identify.

New detectors for both gas and liquid chromatography, based on photochemical and chemiluminescent reactions, will be investigated. Besides continuing the development and the application of these detectors to problems in environmental chemistry, detailed kinetics studies of the reaction mechanisms involved are planned; a better understanding of the reactions themselves could lead to improvements in detection sensitivities and selectivities. Reactions to be further elucidated include (1) the chemiluminescent reaction of sulfur and selenium compounds with molecular fluorine, (2) the photochemical production of hydrogen peroxide from quinones in the presence of oxygenated hydrocarbons such as aldehydes, ketones, ethers, and alcohols, (3) the reactions of furans with singlet oxygen produced in photochemical reactions, and (4) mechanisms of ozone-induced chemiluminescence.

The capillary chromatography/supersonic jet spectroscopy method will be extended in two significant ways. First, the method will be combined with sensitized phosphorescence detection so that nonfluorescent compounds can be detected. Phosphorescence detection will be most useful in the analysis of chlorinated and heterocyclic aromatics. Second, the possibility of using Fourier transform spectroscopy in the UV and visible spectral region to obtain complete excitation spectra at high resolution for each chromatographic peak will be explored. If successful, this development will establish our method as a powerful analytical technique for the rapid, selective multicomponent analysis of complex samples.

Ongoing studies of atmospheric particulate matter will shift to samples that have been collected from airborne platforms over Arctic and Atlantic areas. Samples from the Western Atlantic Ocean Experiment (WATOX) in January 1986 are being analyzed as are others from AGASP–II. The analysis will include further identification and possible quantitation of organic compounds and analysis of changes in concentration and composition as a function of atmospheric conditions, altitude, and location. AGASP–II data may be useful for studying the sources, chemical processes, and possible effects of Arctic haze.

ATMOSPHERIC AND CLIMATE DYNAMICS

In addition to research supported by contracts and grants from Federal and State agencies, a substantial amount of Atmospheric and Climate Dynamics (ACD) research is done with ERL in Boulder. For example, CIRES personnel have made valuable contributions to the remote atmospheric sounding investigations at WPL, and the close interaction of independently supported CIRES researchers at the ESG/Climate Research Program is responsible for the success of the Comprehensive Ocean-Atmosphere Data Set's development. These and other collaborations are discussed in detail elsewhere. This section covers ACD research topics that are supported by other-agency contracts and grants.

Individual projects vary from year to year, but the overall direction of the research is toward increased understanding of interactive processes in three program areas. Within each area, basic and applied research into processes on a broad spectrum of time and space scales attempts to develop a more coherent picture of the Earth's physical environment and its sensitivities to natural and anthropogenic change.

Accomplishments FY 1985

ATMOSPHERE-OCEAN INTERACTION

The interactions between atmosphere and ocean govern heat storage and transport in the climate system. ACD research is largely concerned with the interactive parts of the two media, the boundary layers on both sides of the air-sea interface. Observational and theoretical research projects focus on boundary-layer turbulence, heat storage in the oceanic mixed layer, the roles of boundary-layer clouds in these phenomena and the response of the two layers to variable forcing.

Two major interagency field programs, the Genesis of Atlantic Lows Experiment (GALE) and the Frontal Air-Sea Interaction Experiment (FASINEX), took place in January, February, and March 1986 with significant CIRES involvement. NOAA and NCAR research aircraft were used in both experiments. Oceanographic and meteorological data were obtained to enhance understanding of the development of low-pressure systems off the U.S. east coast (the GALE focus) and to investigate the interactive behavior of atmosphere and ocean in the vicinity of the North Atlantic Subtropical Convergence (the FASINEX goal). Preliminary analysis indicates that these data sets contain unique and valuable information that will be a research resource for several years to come.

The data from FASINEX will be particularly valuable in combination with a limited-area version of the hybrid mixed-layer/isopycnal-coordinate ocean circulation model under development at CIRES. This model is particularly applicable to the FASINEX data because it resolves frontal regions explicitly, without expensive increases in grid-point resolution. During the last year, model development has produced the interesting finding that, except for diagnostic purposes, sea-surface temperature is not particularly relevant; density is the determining factor in the mixed layer's interaction with the deep ocean. This aspect of model behavior is an indication that salinity should be included as another dependent variable in the model.

Both the GALE and the FASINEX data will add new meteorological situations to the boundary-layer turbulence data base that is being accumulated by ACD researchers. These new data sets will complement data gathered previously, by adding new meteorological situations to those already archived. The cloud-topped boundary-layer data from 1985 are an important part of this data base, and their analysis has proceeded for the past year. Data gathered earlier include the Christmas Island data (1984) and several data sets obtained under the auspices of the Equatorial Pacific Ocean Climate Studies Program. Another project, somewhat more interdisciplinary, involves the research interface between global plate tectonics and climate. It is reported here because the tools are climate models that include a simplified air-sea exchange. Numerical experiments were used to investigate the role of continental configurations in determining global climate by studying changes in global temperature, hydrological cycle, and runoff patterns for several idealized continental configurations having the same land area as Earth. Because of strong ice-albedo feedback, colder climates tend to be associated with continents located near the poles. The hydrological cycle, however, is not so easily explained, because it is enhanced by warm temperatures (owing to the dependence of saturation vapor pressure on temperature) but depressed by continents (since surface evaporation is decreased). These experiments are a prelude to more realistic simulations.

CRYOSPHERE-CLIMATE INTERACTION

A major activity at CIRES concerns remote-sensing techniques applied to Arctic studies. Much of the work takes advantage of the resources of the World Data Center–A (WDC–A) for Glaciology (Snow and Ice) and the National Snow and Ice Data Center (NSIDC), both of which are housed at ACD. One of the most important data sets is the Defense Meteorological Satellite Program (DMSP) archive, and a major accomplishment of the past year is acquisition of funding for an automatic digitizing camera, which will allow the DMSP film data at WDC–A and NSIDC to be re-digitized, at any level of resolution, and merged with other data sets. Hence, such projects as those described below will be automated and need not rely on the more subjective methods of the past.

The digitizer purchase will also support the work to be undertaken under the recently funded University Research Initiative (from the Office of Naval Research) to investigate "Arctic Ocean atmosphere - ice system studies." This project, involving CIRES and NSIDC staff and graduate students, will establish links between researchers at the University, the Naval Ocean Research and Development Activity, and the U.S Army Cold Regions Research and Engineering Laboratory.

Other accomplishments of FY 1986 involved work on snow melt on Arctic sea ice and Arctic cloud cover. The first maps of snow melt progression during four summer seasons were prepared from DMSP visible images. Melt categories were calibrated to compute surface albedos, and seasonal albedo trends were determined for the Arctic and marginal ice-covered areas. In addition, data from Nimbus-7's Scanning Multifrequency Microwave Radiometer (SMMR) were shown to be applicable to early identification of snow-melt initiation by comparison with DMSP data. Springtime cloud cover in the Arctic was shown to be sensitive to synoptic controls, rather than being affected by simple climatological changes as is often assumed. Manually analyzed DMSP data were combined with synoptic data to develop a comparison of mean sea-level pressure patterns and cloud cover, and further compared with outputs from the NASA/Goddard Institute for Space Studies climate model.

The carbon dioxide "greenhouse" is a continuing source of research problems, and one of the most important is how to determine the onset of a theoretically predicted warming. Lake-ice breakup timing was investigated as a proxy for seasonal temperature trends. Data for lakes in Finland were compared with air temperature data to investigate this possibility, and efforts are under way to determine the feasibility of using operational satellite data, with an image analysis system, to relate freeze-up/break-up dates to climate change. A potential consequence of the carbon dioxide greenhouse is the surging of Antarctic glaciers and ice streams, and theoretical and observational work has addressed this problem. Two Antarctic ice streams that are grounded on the bottom of the Ross Sea were investigated in detail, and their basic and derived characteristics were used as a basis for extensive model experiments of ice-stream flow and surge. Models of the greenhouse effect suggest that sea-level rise could be of the order of 1 m over the next century. The flow models continue to be improved, with particular attention to the characteristics of the ice-stream bed and the basal friction.

INTERACTION OF WAVES AND TURBULENCE WITH MEAN FLOWS

To a large degree, the definitions of "turbulence" and "mean flow" depend on the frame of reference. Thus, interactions of the two can involve processes on a wide range of spatial and temporal scales. Work at ACD spans scales from global waves and turbulence in the stratosphere to fine-scale turbulence in the boundary layer. In the former category, accomplishments include the following:

- Study of the "Winter Anomaly" in the middle atmosphere, its relationship to nitrous oxide transport by planetary waves and the mean circulation, and its modeled effect on radio propagation.

- Model studies of the roles of stationary and planetary waves during stratospheric warming events and their temporal evolution.

- Investigations of the role of breaking gravity waves in the deposition of zonal momentum into the upper atmosphere, using the Poker Flat mesosphere-stratosphere-troposphere radar.

- Technical development of a method to use the WPL wind Profilers to determine mesospheric wind soundings without interrupting the Profilers' normal (tropospheric wind) operations.

Study of the interactions of turbulence and waves with mean flows on small scales in the boundary layer continues with analysis of observations from the Boulder Atmospheric Observatory. This analysis has proved to be very useful in the investigation of the relationships of mean atmospheric structure and turbulence. In particular, it has led to the derivation of a theoretical relationship between the temperature variance and the local stability and to a similar relationship involving the velocity variance. This work has important implications for the WPL remote-sensing programs, as it may lead to a method for improving the vertical resolution of the Profiler system.

Plans FY 1987

Experimental activities will continue with the fielding of the first marine stratocumulus intensive field observation program in the First ISCCP Regional Experiment (FIRE; ISCCP is the International Satellite Cloud Climatology Project). FIRE is another multi-agency program involving CIRES researchers. The marine stratocumulus segment of FIRE is oriented toward understanding satellite observations of these clouds ("What, precisely, do the satellites see?"), and CIRES researchers will use the opportunity to add to the boundary-layer turbulence data base.

Given the quantities of data gathered in the last two years, and to be obtained next summer, analysis will necessarily become a major activity in FY 1987. Both the FASINEX and GALE data will be subjected to the conditional sampling and budget analyses that have become a standard with CIRES researchers, and, as a theoretical complement to this work, a recently developed statistical/dynamical convective element ("plume") model will be applied to the data. This will allow comparison of the "conditionally sampled" model results with observations, to validate the model. The goal of this research is to understand the response of convective events, the macro-view of which is turbulence, to varying forcing.

The production phase of the ocean modeling project will begin in FY 1987; experiments are planned on the circulation in the North Atlantic basin, the Equatorial Pacific, and the South Atlantic, in addition to the FASINEX comparison work. This work will be facilitated by NCAR's new vector-processing supercomputer, a CRAY XMP.

Research into the effects of continental configurations on the climate will continue with the introduction into the NCAR climate model of a continent conforming to the "Pangaea" of the Triassic (approximately 240 million years ago). Experiments similar to those already conducted will be performed, and the carbon dioxide content will be varied. In this way, we will also address the question of early greenhouse effects in relation to the effects of atmosphere-ocean forcing of the climate.

The initial work undertaken under the auspices of the University Research Initiative will be the analysis of sea-ice characteristics as determined by a variety of remote-sensing instruments (microwave, visible, infrared, sonar). Jointly with the Lamont-Doherty Geological Observatory, mapping of the snow melt in the Arctic based on DMSP analyses will continue.

WDC-A and NSIDC activities will build on work begun in FY 1986 with increased development of the Cryospheric Data Management System (CDMS) supported by NASA. Sea-ice data sets from the Special Sensor Microwave/Imager will be first to be analyzed under the new CDMS format, and a major project will be the re-gridding of the SMMR data on the new grid. A passive microwave data workshop is planned for early in FY 1987.

Analysis and modeling of Antarctic ice streams will continue with extension to other ice streams and a new basal sliding parameterization. In addition, the data set of basic and derived ice sheet characteristics will be extended to the entire Antarctic continent with 20-km resolution. On larger scales, model studies will be conducted to complete the investigation of transient/stationary wave coupling and the time-dependent effects of these waves on the mean flow in the upper atmosphere. Platteville radar data will be used to infer the effects of gravity wave momentum fluxes on the mean wind and the phenomenon's relationship to convective activity.

The small-scale work will be extended to test the feasibility of using the Stapleton radar wind Profiler to sense temperature and velocity variance below the Profiler's nominal resolution in the vertical. The Profiler data will be compared with sonde data, and the measurements from the 300-m tower will be extrapolated to higher levels. In addition, the theoretical background of this inversion technique will be expanded to include horizontal wind shear.

SOLID-EARTH GEOPHYSICS

Accomplishments FY 1986

Solid-earth geophysics continues to be a major component of CIRES research. Some support is provided by the National Geodetic Survey and the NOAA National Geophysical Data Center. However, most support comes from outside NOAA (e.g., USGS, NSF, NASA, DOD, LANL).

Active research areas in geophysics include theoretical and observational geodesy and geodynamics, laboratory studies of rock failure and rock properties under high stress, isotope geology, earthquake prediction and other observational seismology, theoretical studies of wave generation and propagation, engineering seismology, and global geology.

GEODESY/GEODYNAMICS

Ongoing research in geodesy and geodynamics is directed toward both global and regional problems. Efforts on the global scale include attempts to improve our knowledge of the fluid velocities and boundary topography of the Earth's core, mantle anelasticity at periods between 12 hours and several tens of thousands of years, and large-scale mantle convection. Work in these areas has involved analytical and numerical modeling efforts, combined with results from highly accurate space geodetic techniques, such as laser ranging to artificial satellites and interferometric observations of radio waves emanating from deep space.

Regional studies have focused on monitoring and interpreting local and regional crustal deformation, and on determining underlying material properties. Two-color laser distance-measuring instruments (geodimeters) have been built and installed near Parkfield, California, by CIRES scientists. The data from these instruments are processed at CIRES as they are acquired, to determine the time-dependent, local horizontal deformation in this tectonically active area. In another regional project, data from borehole tiltmeters installed in Yellowstone Park are being used to learn about the geological structure beneath the park.

An important component of CIRES research in geodesy/geodynamics is the University Navstar Consortium, a multi-university consortium run by CIRES Fellows. The responsibility of the consortium is to assemble, test, and administer the deployment of instrument packages that use radio signals from the DOD Global Positioning System satellites to determine distances between points on the Earth's surface. The scientific objective is to monitor crustal deformation in tectonically active areas. The consortium took delivery of three TI4100 receivers in May 1986. The receivers theoretically enable terrestrial baselines to be measured to an accuracy of approximately 1 cm horizontally and 3 cm vertically over distances of several hundred kilometers. The practical accuracy of the system is under investigation. As part of the investigation the equipment was used to determine baselines between

Caribbean Islands in a joint study with JPL, to measure distances to offshore islands in California, and to measure baselines in Iceland (in an international project funded by NSF). The Iceland project, the biggest experiment of its kind ever undertaken, involving 24 receivers across the Northern Hemisphere, generated more than 100 Mbytes of data, which were processed in record time in Switzerland.

SEISMOLOGY

Seismology achieved several breakthroughs in 1986. One CIRES seismologist led a group of U.S. scientists who negotiated an agreement with the Soviet Academy of Sciences for an exchange of seismograph arrays to be placed near Soviet and U.S. underground nuclear test sites. Under this agreement, U.S. seismographs have been installed in the Soviet Union, where they have recorded earthquakes and at least one U.S. nuclear explosion. These data are extremely important for more accurate estimates of the yields of past Soviet nuclear explosions. Determining whether the Soviet Union has violated the SALT II agreement depends on accurate yield estimates. For the future, the seismographs in the Soviet Union will allow the monitoring of much smaller Soviet nuclear tests than have been hitherto detectable. Much of the funding for past and present detection and discrimination work has come from the United States Air Force. Funding for the monitoring within the Soviet Union is provided by the Natural Resource Defense Council. Another notable achievement was the successful prediction by a CIRES seismologist of a magnitude-7.9 earthquake, which occurred on 7 May 1986 and ruptured approximately 200 km of the plate boundary near Adak Island in the Aleutians. On the basis of seismic quiescence (a substantial reduction in the number of small earthquake occurrences) as evident in data from the CIRES network of seismograph stations in the Aleutians, an earthquake larger than 7 off Adak Island had been predicted more than 2 years ago for October 1985. Although some of the details turned out to be incorrect, most seismologists consider the prediction a success. This is the first time that a large earthquake in the United States has been predicted correctly.

A CIRES seismologist was also involved in the first successful earthquake prediction for the San Andreas fault. The prediction had specified two approximately 8-km segments of a 100-km portion of the San Andreas fault as locations for magnitude 5 $\pm$ 0.5 earthquakes before the end of May 1986. The Stone Canyon earthquake of 31 May 1986 measured 4.7 on the Richter scale and its aftershocks filled the specified area exactly. Following this success, a new prediction has been issued for another magnitude 5 earthquake to occur during 1987 in the Bitterwater Valley segment of the San Andreas fault. These predictions are also both based on the quiescence hypothesis.

Both the Adak and the San Andreas predictions drew from results of several years of studying precursory seismicity patterns and of developing tools for defining precursory anomalies. This work was funded through the NSF and the USGS.

The engineering seismology program, funded by NSF, has included studies of surface motion amplification due to topographic features and alluvial valleys, and investigation of the dynamic response of extended underground structures like pipelines and tunnels. Work has also continued in wave dispersion and attenuation in media with microstructures (e.g., cracks), and in wave propagation in layered media.

LABORATORY GEOPHYSICS

FY 1986 marked the first year of research efforts in isotope geology at CIRES. A modular clean room was constructed and placed in routine use for rock dissolutions and element extractions. Projects supported in part by NSF, USGS, and the Los Alamos National Laboratory were initiated, including (1) Nd and Sr isotopic studies of Mesozoic and Tertiary granite in central Alaska, (2) isotopic studies of Tertiary silicic volcanic rocks in Nevada and Utah, 3() Nd isotopic determinations of the provenance of Precambrian and Cambrian clastic sedimentary rocks in western North America. Funds from NSF, CIRES, and the University of Colorado were also obtained for the acquisition and housing of a multicollector solid-source mass spectrometer.

The rock physics group has been investigating problems related to rock deformation and fracture. The research has diverse applications, including understanding earthquake-related mechanisms, explaining the observed anelastic and anisotropic properties of the Earth's interior and their relation to flow within the Earth, and the disposal of hazardous wastes. For example, one experiment is directed toward understanding the stresses within the mantle that drive tectonic plates. The attenuation of seismic waves in the mantle is apparently due to dislocations within mantle crystals. The equilibrium dislocation density is a function of the stress within the mantle. In the experiment, which is run on rock samples at temperatures in excess of 1000°C to correspond with mantle temperatures, the attenuation of elastic waves in the seismic frequency band is determined as a function of dislocation density. The results may make it possible to infer mantle stresses from seismic attenuation observations.

GLOBAL GEOLOGY

The global geology group made progress on three fronts. First, the group produced a new set of plate tectonic maps for the past 250 million years in 10-million-year periods. The results show much more active global sea floor spreading during the Triassic than has previously been assumed. Second, the group discovered a 150-million-year cycle in various sedimentation parameters. The cause of the cycle is not yet clear, but it is probably related to a similar cycle in the climate. Third, the group developed numerical methods for taking present-day distributions of sediments and rock and restoring them to their original sites of erosion. Previous efforts of this kind grossly underestimated the sediment cover of the continents in the geologic past.

Plans FY 1987

Most of the activities described for FY 1986 will continue into 1987. For example, the seismology group in CIRES will continue in interpreting data obtained from the seismic array in the Soviet Union and in its efforts related to earthquake prediction.

The 1986 Adak earthquake will be the subject of intense study. First, much can be learned about fault plane asperities and the tectonic interpretations thereof from the differences between the predicted and actual characteristics of the earthquake. Second, the seismic characteristics of the boundary between ruptured and unruptured fault plane will be examined in detail; the western edge of the area that ruptured during the earthquake was well recorded by the CIRES seismic network. Third, time variation of seismicity and stress patterns from the period immediately preceding the earthquake will be searched for possible short-term precursors.

Work in geodesy/geodynamics will also continue along the lines described for FY 1986. Some additional modeling efforts will focus on understanding the crustal deformation caused by changes in atmospheric pressure, in ground water storage, and in sea level. Work has also begun in using ocean tide gauge data to investigate long-period tides in the ocean. Several important solid-earth interpretations of geodetic data assume those tides are in equilibrium. That hypothesis will be tested.

Observational projects will be initiated using the University Navstar Consortium receivers, in response to NSF funding. The locations of these initial projects are under review by NSF but all are directed at improving our understanding of crustal deformation processes related to Plate Tectonics and earthquake mechanisms. The consortium will continue to develop software and hardware (radiometer) to increase system accuracy.

The new fiscal year will also see at least two new projects in observational geodesy. In one, a 1-km-long two-component long-baseline water pipe tiltmeter will be installed at Mammoth Lakes in California. The tiltmeter will be within the Long Valley volcanic caldera and is intended to monitor inflation and deflation of the buried magma chamber. In the other, a new digital creepmeter is being tested that is triggered by displacements greater than 20 μm on an active fault. The resolution of the instrument is 10 μm, and its length is considerably greater than the typical 10–20 m of present creep-

meters. The instrument is destined for use on the San Andreas Fault in central California and on the Xianshuihe Fault in China.

For isotope geology, the recently funded solid source mass spectrometer should be fully operational by June 1987. The new mass spectrometer and continuing support from NSF, USGS, and LANL will allow projects already initiated to be carried out directly at CIRES. Funding is being sought for projects involving the use of isotopic tracers in hydrothermal fluids (at the Bingham copper deposit in Utah) and the use of Nd isotopic "stratigraphy" in tectonic reconstructions (in British Columbia).

The rock physics group has begun a combined experimental and theoretical study of wave propagation and scattering in layered anisotropic plates. The experiment uses a high-frequency, absolute displacement transducer developed in-house, which allows precise ultrasonic signed measurements. Work is also progressing on studies of phase transformations in ceramic materials under stress and in the nondestructive evaluation of failure in concrete.

The global geology group, like other CIRES groups, will expand on its 1986 efforts. The plate tectonic maps will be revised and used to analyze the time-dependent global heat flux from the Earth's interior. Methods will be developed for using the observed mass-age distribution of global sediments to estimate the rate at which sediments were transported over the Earth's surface in the geologic past. The numerical methods for reconstructing sedimentation systems will be used to produce paleo-maps of Africa and parts of North America.

CENTER FOR EARTH OBSERVATIONS AND REMOTE SENSING

The Center for Earth Observations and Remote Sensing (CEORS) was founded in late 1985. CEORS acts as a focus for interdisciplinary studies making use of remote-sensing techniques. The Center is directed by Alexander F. H. Goetz, who came to the University of Colorado from the Jet Propulsion Laboratory, Pasadena, California.

The development of the Center was assisted by a receipt grant from the W. M. Keck Foundation together with matching funds from the University of Colorado. The funds have been used to create an image-processing facility based on three stand-alone GPX/MicroVAX II workstations. A laboratory for sample analysis using spectroscopic and x-ray diffraction techniques is under development along with a color darkroom facility. At present, CEORS employs four staff and three graduate students.

The long-term goal of CEORS is to act as a focus for global studies of the Earth in the areas of quaternary geology and paleoclimate studies, land-atmosphere interaction, vegetation dynamics, and hydrology, through the use of remote-sensing data from airborne and spaceborne platforms. Three additional University faculty positions have been allotted to the Center and will be filled in the next two years. The presence of CEORS within CIRES offers a unique opportunity to make contributions to the Earth-System Science and International Geosphere-Biosphere programs.

CIRA

The Cooperative Institute for Research in the Atmosphere (CIRA) was formed in 1980 between Colorado State University (CSU) and the National Oceanic and Atmospheric Administration (NOAA) to increase the effectiveness of atmospheric research of mutual interest to NOAA, CSU, the State, and the Nation. Additional objectives are to provide a center for cooperation in specified research programs by scientists from Colorado, the Nation, and other countries, and to hasten the training of atmospheric scientists. All CSU or NOAA organizational elements are invited to participate in CIRA's atmospheric research programs. Initial participation by NOAA has been through the Environmental Research Laboratories (ERL) and the National Environmental Satellite, Data, and Information Service (NESDIS). At the University, the Departments of Atmospheric Science, Civil Engineering, Economics, Electrical Engineering, Psychology, Recreation Resources and Landscape Architecture, and Statistics

are involved in CIRA activities. As its research themes, CIRA concentrates on air quality, cloud physics, mesoscale studies and forecasting, satellite applications, climate studies, agricultural meteorology, model evaluation, and economic and societal aspects of weather and climate.

Five NOAA scientists in residence at CSU constitute the Regional and Mesoscale Meteorology (RAMM) Branch of NESDIS' Applications Laboratory. They lead the CIRA collaboration with ERL in short-range weather forecasting research.

Accomplishments FY 1986

CIRA has received many research grants from various agencies, including the U.S. Army Research Office, National Aeronautics and Space Administration, NOAA, and the National Science Foundation. The staff of CIRA now numbers 17 Fellows, 3 Postdoctoral Fellows, 7 Senior Scientists, 12 Research Associates, 3 Research Coordinators, and 8 support staff.

During June a workshop was held for all CIRA research personnel. Attended by 31 researchers from CIRA, CSU, and NESDIS/RAMM Branch, the workshop helped to stimulate and nurture new and existing research concepts. A second timely workshop entitled "Acid Deposition in Colorado—A Potential or Current Problem; Local Versus Long-Distance Transport Into the State" was held in August. This "by invitation only" workshop was attended by 30 researchers from across the Nation and Canada with a specific interest in acid deposition.

Plans FY 1987

Plans include continued collaboration of NOAA, NASA, NSF, and CSU scientists and students in research related to CIRA's mission. We plan to continue expansion of our staff; two new Postdoctoral Fellows will join CIRA by January 1987.

A Center for Geosciences supported by the U.S. Army Research Office is being established at CIRA. The 5-year award will be administered by CIRA and is to be shared among seven departments within the University: Atmospheric Science, Civil Engineering, Earth Resources, Electrical Engineering, Forest and Wood Science, Physics, and Psychology. It is anticipated that construction on the new Center will be completed by spring 1987 and will become part of the CIRA facility at the University's Foothills Campus. The technical components of the Center are in Atmospheric and Surface Remote and In-Situ Sensing, Atmospheric Modeling of Meteorological Parameters and Dispersion, Hydrology including Hydrologic Modeling, and Geoscience Information Extraction.

SATELLITE CLOUD CLIMATOLOGY PROJECT

Accomplishments FY 1986

Since 1984, CIRA has participated in the International Satellite Cloud Climatology Project (ISCCP) (part of the World Climate Research Programme) as a Sector Processing Center. GOES-6 data have been collected, and we are contributing to the ISCCP validation program by preparing our own cloud estimates for comparison with other estimates.

Plans FY 1987

With collection complete, plans are to analyze all recorded data extensively.

SEVERE WEATHER RESEARCH

Accomplishments FY 1986

CIRA is making progress in severe weather research and satellite sounding applications under NOAA grants. Subjects of current efforts include the following:

- Uses of Research Rapid-Scan Data (RRSD) and satellite sounding and microwave data to diagnose the severe storm and its environment.
- Planning for and participation in the Cooperative Huntsville Meteorological Experiment (COHMEX).
- Colorado State University VAS data ingest and applications.
- Nowcasting in Colorado.
- Development of training aids and techniques for mesoscale forecasting.

In conjunction with severe weather research, CIRA is develping satellite imagery products. CIRA is working with ERL's Program for Regional Observing and Forecasting Services (PROFS) and NASA to investigate the uses of high-resolution imagery for analysis and forecasting.

Plans FY 1987

- Work in the above-mentioned areas will continue.
- A PROFS interactive workstation and a VAS data utilization terminal will be installed at CIRA to aid in data and product evaluation, and in development for regional and mesoscale applications.
- Methods for integrating satellite sounding and image data into mesoscale models will be investigated.

AIR QUALITY—JOINT RESEARCH WITH THE NATIONAL PARK SERVICE

Accomplishments FY 1986

A cooperative effort of the National Park Service (NPS), NOAA, and CIRA/CSU is in its fifth year. The primary emphasis is on air quality, and various CSU departments such as Statistics and Psychology are participating in the effort to determine, evaluate, and analyze the effects of impaired air quality in the Grand Canyon and other National Parks.

Plans FY 1987

CIRA will continue its research cooperation with the NPS under five grants. Approximately eight NPS employees will be housed in the new CIRA facility at the CSU Foothills Campus.

CIMMS

The Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) was established in 1978 as a joint venture of the University of Oklahoma (OU) and the National Oceanic and Atmospheric Administration (NOAA) through the National Severe Storms Laboratory (NSSL) of the Environmental Research Laboratories (ERL). CIMMS is administered by the University. The Council of Fellows, consisting of the University faculty and NSSL staff, helps formulate the policy of CIMMS. The Advisory Board of CIMMS meets annually to evaluate achievements and goals and to make recommendations. The Board includes representatives from OU, NOAA, and outside organizations.

Program objectives and activities of CIMMS are selected to achieve the general goals of NOAA (by complementing the research activities of NSSL at Norman), of other NOAA/ERL Laboratories, and the University of Oklahoma.

CIMMS is charged to address the following specific themes:

- Mesoscale models
- Mesoscale dynamics
- Orography and lee cyclogenesis
- Variational optimization analysis and remote sensing

Accomplishments FY 1986

MESOSCALE MODELS

Mesoscale modeling research at CIMMS focused on investigations of optimal analysis techniques and the numerical prediction of severe storms and hazardous weather. Specifically, work was done in the areas of model initialization and data assimilation. Scientists at CIMMS, along with researchers from the OU School of Meteorology and NSSL, began work on a next-generation mesoscale model for the central Oklahoma meteorological community.

Initialization and Assimilation

The CIMMS mesoscale model and the OU version of the Florida State University primitive equation model were used to study initialization and assimilation problems for mesoscale forecasting. Variational initialization was shown to be promising for further studies.

The microsymmetry method was used to construct a two-dimensional horizontal wind field from the radial velocity components detected by a single-Doppler radar wind observation. This method may significantly broaden usage of data from the forthcoming Next-Generation Weather Radar (NEXRAD) observation network.

An initialization and assimilation experiment simulated incorporation of NEXRAD and Wind Profiler observations into a mesoscale forecast model. Considerable improvement of wind and pressure patterns in fronts was obtained.

Next-Generation Mesoscale Model

The objective of the Central Oklahoma Mesoscale Modeling and Analysis (COMMA) project is to use new types of remote-sensing data (such as Wind Profiler, NEXRAD, and satellite data) to deduce a thermodynamically and dynamically sound assimilation method and to develop a next-generation mesoscale model, in a cooperative effort of the Norman, Oklahoma, meteorological community. The development of such a model appears to be timely because of the availability and power of computer resources and numerical techniques, the advancement of theoretical understanding of

mesoscale and convective phenomena, and the new high-resolution data to be available within the next half decade. CIMMS researchers have significant roles in developing this project.

MESOSCALE DYNAMICS

Progress in understanding mesodynamics during the last year was most significant in two areas: (1) Recognition of the important role of conditional symmetric instability on rainband formation and development of other convective systems; (2) laboratory simulation of mesocyclone and tornado-like vortices in vertically sheared flow. In the latter, advanced techniques for velocity measurement were employed, and an apparatus was designed to simulate the vertical shear of the horizontal wind. The new design altered the laboratory tornado vortex chamber so that the inflow air feeding the vortex was caused to veer horizontally with height, in analogy to the sheared environment of a typical tornado-producing supercell storm. A workshop on Modeling of Tornado Vortices was held on 14–15 November 1985 at CIMMS.

OROGRAPHY AND LEE CYCLOGENESIS

Research continued on the processes of alpine lee cyclogenesis, using the Alpine Experiment (ALPEX) data. This research was funded mostly by the National Science Foundation. Emphasis was placed on the effect of the mountains on the mechanisms of vorticity production on the lee side and regeneration of fronts passing over the mountains. Because of the extensive data available from ALPEX, this research is expected to hint at new ideas of genesis and development of short wave troughs, fronts, and severe storms, which occur on the lee side of the Rocky Mountains. The CIMMS mesoscale model was used to produce high-resolution balanced data sets for the study of dynamical processes associated with alpine lee cyclogenesis. In this study, the effects of diurnal heating of the high mountains and high plateau were examined in the development of thermal-frontal depressions and their relation to forcing of convection.

VARIATIONAL OPTIMIZATION ANALYSIS AND REMOTE SENSING

Work was continued to develop efficient and accurate techniques for analysis of remotely sensed data including satellite-sensed radiation, NEXRAD Doppler radar wind information, and ground-based vertical wind profiles. Development of these techniques was recognized as important for timely and proper diagnoses of hazardous mesoscale severe weather and for providing appropriate initialization and assimilation methods for mesoscale forecast models.

Single-Doppler Wind Data Analysis

The microsymmetry method was tested for several selected cases. It showed excellent agreement between known two-dimensional wind fields, and those derived from Doppler radar radial wind velocity by use of the microsymmetry method. It thus became possible to derive two-dimensional wind fields from only NEXRAD-type radial velocity observations. Three-dimensional velocity fields may be obtained from the calculated two-dimensional wind, using the mass continuity equation.

De-aliasing

De-aliasing of radial wind components was investigated by means of an artificial intelligence approach. The approach includes three assumptions: (1) spatial continuity of the velocity field, (2) temporal continuity of the velocity field, and (3) use of a reliable mental model of the wind field. In another NEXRAD-related study, an algorithm to characterize storm severity using divergence measurements at storm top was investigated.

Lidar Data Analysis

Another observing system of interest and of potential use for the future is airborne lidar. Results from our analysis of lidar data were beyond expectations; strong evidence of an entrainment zone

around clouds was observed, and two-dimensional velocity fields obtained from lidar data resolved fine undulations and vortex fluctuations at the edge of a gust front.

Storm Lightning

Storm lightning strikes were studied as a NASA project, using data obtained by instrumented aircraft penetrations of thunderstorms. It was concluded that although the number of lightning strikes to an airplane could be as much as one-third of all strikes, all strikes to an airplane were intercloud portions of discharges rather than return strikes, which have relatively much stronger currents and rise times. An investigation of lightning effects on precipitation, including data analysis of the 1985 season, showed that lightning caused refractive index changes due to shock wave propagation through the radar resolution volume. Another study suggested a parameter for estimating rainfall rate that is better than the parameter used in conventional methods. The parameter is the differential propagation phase shift constant.

International Symposium

In October 1985, CIMMS was host to the International Symposium on Variational Methods in Geosciences co-sponsored by the American Meteorological Society and several other scientific societies. This symposium featured ten internationally renowned scientists as keynote speakers, and more than 40 papers were presented. These presentations related the use of variational mathematical theories and techniques in the presenters' current research. The variational methods presented and discussed in the symposium offered solutions to important problems of Doppler radar data (NEXRAD and Wind Profiler) analysis and initialization and assimilation problems of mesoscale forecast models.

Plans FY 1987

MESOSCALE MODELS

- Continue modeling efforts at CIMMS with NEXRAD Doppler and vertical wind Profiler data, parameterization of diabatic processes and terrain-influenced boundary layers on the mesoscale.
- Further develop the COMMA project, to implement a fine mesh, well-proven, and outstandingly accurate numerical scheme, and a sound microphysical model into a mesoscale forecast model.

MESOSCALE DYNAMICS

- Continue a study on symmetric and conditional instabilities to reveal mechanisms of initiation, development, and decay of severe weather systems.
- Continue laboratory experiments and numerical simulation of tornado-like vortex generation and structure.
- Study turbulent processes in tornado, gust-front, and other mesoscale systems.

OROGRAPHY AND LEE CYCLOGENESIS

- Continue research on the effects of mountains and undulating hills on synoptic and mesoscale weather systems.
- Continue research to discover the mechanisms of boundary layer formation and separation, and surface heating and cooling due to orography, and their influences on the onset of severe storms.

- Develop a more realistic and predictable terrain-influenced boundary layer parameterization for mesoscale models.
- Continue to diagnose the evolution of jet streams and fronts and their interactions with terrain.
- Develop understanding of how terrain-induced mechanisms lead to cyclogenesis, frontogenesis, and severe storm development.

VARIATIONAL OPTIMIZATION ANALYSIS AND REMOTE SENSING

- Continue to develop initialization and assimilation methods of Doppler NEXRAD and wind Profiler data into mesoscale models.
- Simulate NEXRAD and wind Profiler data in a mesoscale forecast model to evaluate their sensitivity in mesoscale analysis and forecasting.
- Continue to test microsymmetry methods for generating two-dimensional horizontal wind fields from NEXRAD-type one-dimensional radial velocity information.
- Continue research on de-aliasing of Doppler wind velocity folding by using time/space continuity and human judgment of the appropriateness of resulting patterns.
- Continue to investigate mechanisms of lightning strikes and their influence on precipitation.

CIMAS

The Cooperative Institute for Marine and Atmospheric Studies (CIMAS) is an association between NOAA and the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) to stimulate cooperative research between the institutions. The two research themes of CIMAS are Climate Variability and Ecosystem Dynamics.

The primary CIMAS staff consists of twelve Fellows who are appointed from RSMAS faculty and NOAA's laboratories in Miami and who conduct collaborative research. Also included in the staff during FY 1986 were six Members, five Associate Scientists, four Research Associates, two Postdoctoral Associates, and ten graduate students. Members of the staff conduct research at the CIMAS building, other laboratories on the RSMAS campus, and NOAA laboratories. CIMAS also conducts research through partial support of visiting collaborating scientists who augment the expertise at RSMAS and NOAA. During FY 1986 the visiting scientists provided more than 7 man-months of collaborative research and 31 lectures.

CIMAS began publishing the Tropical Ocean–Atmosphere Newsletter (TO–AN), previously published by AOML and JISAO. TO–AN promotes rapid dissemination of information about contemporary activities and ideas on topics of importance to large-scale tropical air-sea interaction in relation to global climate.

CLIMATE VARIABILITY

Research on climate variability concerned ocean processes in Subtropical Atlantic Climate Studies (STACS), tropical ocean and atmospheric processes in Equatorial Pacific Ocean Climate Studies (EPOCS), and atmospheric carbon dioxide (CO_2) loading.

Accomplishments FY 1986

SUBTROPICAL ATLANTIC CLIMATE STUDIES

Climate research in the subtropical Atlantic Ocean consisted of (1) local forcing mechanisms for the temporal variability of the ocean transport at the Florida Straits, (2) moored current meter observation collection and modeling, and (3) Pegasus ocean profiler observation collection and analysis.

In describing the annual forcing of the Caribbean Sea by the curl of the wind stress and the associated response in that basin's thermal structure, particular attention has been given to the forcing over and the response of the Cayman Basin in the western Caribbean. This is because the area–integrated curl of the wind stress over the Cayman Basin was found to be highly correlated (0.95) with the annual variation of the mass transport at the Florida Straits. Such a strong correlation suggested a causal connection. The problem addressed was the identification of the mechanism by which the flow is accelerated and the transport increased. Conservation of mass and momentum of the basin requires that the basin's response be nonlinear, for the flow through the basin to be enhanced. To investigate this, the annual cycle of the Ekman pumping over the basin was decomposed into its principal components (EOFs). A similar set of calculations was done for the annual cycle of the basin's thermal structure. The analyses show these results:

- For both the forcing over and the response of the Cayman basin, more than 80% of the variance is contained in the first principal component.
- The normalized variance of the first principal component for both the forcing and the response are equivalent, which implies that the energy source of the response is the forcing function since, if energy is propagating into the Cayman Basin, it is contained in the higher order components.
- The phase of the first empirical mode of the forcing is determined from contributions at the annual and semi-annual periods, but the response has a significant additional contribution by waves at periods of 4 months.
- This latter observation is consistent with an energy transfer from forced waves at the annual and semi-annual periods to waves at the 4-month period by nonlinear wave-wave interaction, and this interpretation is buttressed by the second result above.

Four current meter moorings were deployed in March 1986 in the western boundary region east of Abaco Island along 26°30'N. The westernmost mooring, at 617 m depth, carried a buoy-mounted, upward-looking acoustic Doppler current profiler (ADCP) to measure the current profile in 8-m vertical intervals to within a few meters of the surface. The plan is to retrieve this instrument during the fall 1986 cruise. The three other moorings of that array are equipped with Aanderaa and vector-averaging current meters at various depth levels between 150 m below the surface and 500 m above the bottom. The instrument distribution is aimed at measuring both the near-surface circulation down to approximately 1000 m and the southward countercurrent running below 1500 m.

An experimental study consisting of the first evaluation of buoy-mounted ADCPs, one working at 150 kHz and the second one at 75 kHz, moored at the STACS site near 27°N, was carried out in January 1986. The study showed that with the 75-kHz system the vertical range exceeded 600 m; with the 150-kHz system the range was about 350 m. Horizontal current data quality was good from both instruments, and there was an indication that these devices might be useful for vertical convection studies.

A study aimed at explaining Florida Current meandering was conducted by using a frequency-domain empirical mode analysis applied to the station data of the STACS–V moored current meter array. The result was that there are apparently cross-channel modes that are transport-efficient (i.e., in phase across the channel) and coherent with the local meridional wind stress components; that there are meandering modes with dominant energy at 12 and 5 days that do not affect transport much and are not coherent with wind stress. With a simple coastal response model driven by the along-channel windstress we determined that there is surprisingly high coherence of modeled transport with actually measured Florida Current transports at periods ranging from days to seasons.

Analysis of the major part of the STACS Florida Current experiment has been completed. The total data set from Pegasus ocean current profilers deployed by RSMAS and NOAA/AOML has been analyzed. In addition to being useful for calibrating other indirect methods (e.g., current meters and electromagnetic cables) of measuring fluxes of heat and mass in the Florida Current, the data have provided significant results of their own. The yearly transport signal in the Florida Current has been found to exhibit a more complicated variation than the simple annual harmonic observed earlier. In particular these data (together with other time series measurements) show a rapid transport decrease in the fall and a secondary minimum in the spring. The average transport is $(31.7 \pm 3.0) \times 106\ m^3s^{-1}$, slightly greater than that observed previously to the south. This fact may indicate a small net input to the Florida Current from the Northwest Providence Channel. The net average northward heat transport estimated from these data is $(1.29 \pm 0.21) \times 10^{15}$W, in good agreement with, although somewhat smaller than previous results obtained by Hall and Bryden. An analysis of the energy conversion terms in the Florida Current indicates that the current is stable; however, these terms are quite small in relation to the total perturbation kinetic and potential energy.

The variability and structure of currents near Little Bahama Bank and Great Bahama Bank were analyzed using Pegasus and shipboard acoustic Doppler current profiler data to determine how these variations are related to fluctuations in the Florida Current as a whole. It was found that meanders of the current can excite baroclinic waves trapped against Little Bahama Bank. These waves tend to reverse the typical northward shear in the Florida Current and on occasion can even cause southward flow (as observed during one cruise) near the boundary. Eddies generated in the Northwest Providence Channel by this reverse flow have been observed in satellite images but have not before been seen in direct measurements.

TROPICAL OCEAN AND ATMOSPHERE STUDIES

Climate research on tropical oceanic and atmospheric processes consisted of (1) developing a structure function to be used initially for ocean velocity components, (2) evaluating the ocean heat budget using drifting buoys, (3) adding dissipation effects to the AOML data assimilation model (ADAM), and (4) analyzing the general circulation model (GCM) at the National Center for Atmospheric Research (NCAR). In addition, a weekly report including a map of buoy trajectories and temperature anomalies for the equatorial Pacific and Indian oceans has been produced.

Research on analytical techniques for processing drifting buoy data led to the determination of a structure function that is less sensitive to data defects than the autocorrelation function. The results show that the structure function using velocity components and a larger part of the available equatorial Pacific Ocean data for the meridional component saturates within about 10 days, indicating the existence of a well-defined autocorrelation that can be computed directly from the structure function. Preliminary estimates of the decorrelation

times for the meridional component are on the order of 5 days or less for each hemisphere. In the Southern Hemisphere the structure function for the zonal component saturates at about 50 days, which suggests a decorrelation time of about 10 days; the Northern Hemisphere zonal component exhibits a somewhat uncertain saturation at about 100–110 days, with an implied decorrelation time on the order of 20 days.

Preliminary estimates of net and local heating and advective processes for a region from the Equator to 10°S and from 90°W to 130°W were obtained using the heat balance equation and drifting-buoy data. The preliminary results were based on a mixed layer of assumed constant thickness because mixed layer thickness data were not yet available.

Dissipation effects were added to ADAM. An eddy viscosity/diffusivity model was used to model the turbulent exchange of momentum/heat in the vertical direction. In the inviscid version of ADAM the vertical dependence was separated out of the equations by using vertical structure functions. Hence, the eddy viscosity and eddy diffusivity were formulated, so to make this separation still possible. The effect on the equatorial wave equations was the addition of a damping term. Dispersion curves were obtained to decide on the modeling of this term. Numerous model runs were made with and without dissipation in an attempt to verify the model additions, especially at the boundaries, with some success.

Progress on the analysis of GCM simulations performed at NCAR has been in two areas: (1) analysis of the model's response to the evolving sea-surface temperature (SST) pattern observed in the equatorial Pacific during the 1982–83 El Niño/Southern Oscillation (ENSO) episode; and (2) analysis of the tropical 30–60 day oscillation in a 1200-day, perpetual-January simulation.

With respect to the first topic, five independent simulations of the 1982–83 ENSO episode were completed with a version of the GCM that incorporates the full seasonal cycle. The SST distributions in the equatorial Pacific (longitudes 100°E to the west coasts of the Americas, latitudes 30°N to 30°S) during the period were those resulting from the addition of the observed SST anomalies to the GCM's climatological, seasonally varying SST pattern. The control case, against which each of the experiments is compared, consists of an ensemble of runs with the climatological SST. The results are in the form of maps of the difference between seasonal (3-month) average fields in the five-member, ensemble-average experiment and the same fields in the five-member, ensemble-average control. The results show that already in the summer of 1982 there is a region of anomalously high precipitation near the dateline in the model and a region of anomalously low precipitation over Indonesia extending northeastward across Northern Australia. By the fall of 1982, the region of excessive precipitation has shifted eastward and become more extensive. In the winter of 1982–83, the excessive precipitation is widespread along the Equator with a peak intensity of 4 mm per day near longitude 140°W. The observed Northern Hemisphere climate anomaly in the winter of 1982–83 consisted of a deep low pressure in the Pacific and a high pressure over northeastern Canada. Some elements of this pattern are evident in the model simulation, but there are important differences. The model's negative anomaly in the Pacific has a rather small amplitude, and the positive height anomaly over North America is to the west of that observed. Inspection of the individual realizations reveals that there is much inter-sample variability in the simulation. We concluded from these results that the observed pattern in the 1982–83 episode was one of several possible realizations.

The 30–60 day oscillation was first identified by Madden and Julian about 15 years ago. On the basis of spectral analysis of the 200-mb wind field at a number of equatorial stations, they hypothesized an eastward-propagating pair of circulation cells in the equatorial plane. Recent studies suggest that the oscillation appears to have middle-latitude manifestations of some potential importance for the understanding of intraseasonal fluctuations in winter climate patterns. Our interest has been the study of the oscillation as it appears in the GCM as

a means of evaluating the scheme that parameterizes tropical convective heating. A 1200-day record from a perpetual-January simulation was analyzed to determine whether there is present in the model's tropical troposphere an oscillation in the 30–60 day range that has some of the features of the one observed in the atmosphere. The oscillation is indeed present in the model as an eastwardly propagating signal with a speed close to that observed. Power spectra do not show a peak as prominent as that observed. We conclude from our analysis that the oscillation is weakly coupled to the model's tropical convective heating.

CARBON DIOXIDE LOADING STUDIES

During the past year, extensive analysis of Ka-band aperture side-looking airborne radar (SLAR) imagery of sea ice and internal waves has been conducted. The analysis has been carried out using a specially configured microcomputer. The computer essentially "grabs" a frame from a television camera source and digitizes and displays it in a 512 × 480 pixel format; the digital representation consists of 256 gray scales. The image-processing software allows calculation of intensity histograms, area calculations of specified intensity ranges, enhancements, and two-dimensional fast-Fourier transforms. With this system, analysis of the Marginal Ice Zone Experiment of 1984 (MIZEX–84) progressed as follows:

Ice Concentration Studies

Ice concentration for 22 June derived from the SLAR imagery was compared with coincident imagery obtained with the NASA CV990 passive microwave system. The initial analysis, though somewhat crude, is within 1–2% agreement with the CV990 data. These data have been provided to NASA for further comparison with vertical photography obtained during a low-level pass of the CV990.

Internal Wave Studies

Internal waves were imaged on numerous occasions by the SLAR. The internal wave signatures consisted of patterns within the marginal ice zone established by concentrations of small 10–100 m floes as well as by "rough–slick" zones in the open water areas. Brunt–Väisälä frequencies for internal waves in nearby regions, calculated from CTD data obtained by ship, indicated first-mode frequencies of 6–12 cycles per hour. This is consistent with wavelengths of kilometer scale and smaller as observed by the SLAR. An interesting characteristic of the two-dimensional FFT analysis of the SLAR imagery was the bandwidth of the spectra. In many instances, only several wave fronts with preferred spacing were observed. At other times, a wide band of wavelengths from about 20 m to 2 km was observed. Internal wave signatures were observed during surface wind conditions, which ranged from near calm to 12 m s^{-1}.

Ice Roughness

A low-altitude peculiar roughness signature of the ice was found in the SLAR imagery. This signature seems to be associated with a scattering mechanism peculiar to sharp edges. For low-altitude SLAR imagery, incidence angles are typically greater than 70°. At these angles, all edges of the large floes exhibit large radar signatures. Ridge structure also produces a large signature, whereas the vast flat area of the snow-covered floe produces a much lower signature. The result is a bimodal histogram of radar return. In the region of small floes, the higher lobe of the histogram is associated with the floes, and the lower lobe is sea return. In the inner MIZ, the higher lobe is associated with ridge, edge, and brash ice of the interfloe region, and the lower lobe is sea and smooth floe return.

Measurements of the drag coefficient produced by small and large floes were reported. The highest drag coefficients (about 4–5 × 10^{-3}) were found to be associated with small

floes and with ridge structures on large floes. When these results are applied to area calculations of rough ice regions from the SLAR imagery, the mean drag coefficient of the outer MIZ correlates directly with concentration and is about 3×10^{-3} ; the inner MIZ is also about 3×10^{-3}. The transition region of closely packed small (10–100 m) floes with intermittent medium-size floes(about 1–2 km diameter) has the highest drag coefficient, about 5×10^{-3}.

Plans FY 1987

SUBTROPICAL ATLANTIC CLIMATE STUDIES

During the end of the fall 1986 cruise, the moored acoustic Doppler current profiler (ADCP) off Abaco Island will be retrieved. In March 1987, the other three moorings of the Abaco line will be retrieved and two new moorings deployed in their place to extend the time series. Later during the same cruise, two ADCP moorings and Pegasus profiler stations will be deployed in the Caribbean inflow regime, between Barbados and Trinidad-Tobago Islands. Deployment of pressure gauges on either side of this inflow regime is planned as well.

The priority for analytical work will be on quick processing and first analysis of the records retrieved off the northern Bahamas in November 1986 and March 1987. Transport time series will be constructed from these moored data in combined analysis with the conductivity, temperature, and depth (CTD) and Pegasus profiling data.

The analysis of Florida Current variability will continue, applying spectral mode techniques to other data sets and establishing quantitative relationships to wind forcing. The STACS data set from the Florida Straits will be analyzed in conjunction with the moored data from positions downstream obtained simultaneously in other programs. Model studies of the combined Atlantic-Caribbean-Florida Current system have also begun, using the Anderson-Corry model and driving it with historical and actual winds of the STACS period.

TROPICAL OCEAN AND ATMOSPHERE STUDIES

Research on structural functions will continue along with drifting-buoy data analysis. The emphasis will be on the largest space scales and annual and interannual time scales.

Research on the AOML data assimilation model will focus on ways to reduce the number of iterations in the conjugate gradient algorithm.

Analysis of the 1982–83 ENSO simulations will be completed. While this activity is in progress, analysis of the 1976–77 ENSO simulations will commence. The observed middle-latitude climate anomalies during the boreal winter were quite different for these two episodes. The objective of the work is to investigate the extent to which the location of the tropical SST anomaly influences the nature of the model response. The influence of middle-latitude SST anomalies in modulating the response in each of these winters will also be examined.

CARBON DIOXIDE LOADING STUDIES

No further work is planned.

ECOSYSTEM DYNAMICS

Ecosystem dynamics research concerns the processes related to tropical and subtropical fish stock variability, especially recruitment mechanisms, fishery dynamics, and environmental chemistry.

Accomplishments FY 1986

RECRUITMENT MECHANISMS

A larval fish index for Gulf of Mexico bluefin tuna and estimates of its spawning stock size were developed. An interactive computer program to calculate unbiased estimates of the mean and variance of samples that follow the delta distribution (characteristic of ichthyoplankton) was developed in conjunction with this bluefin work. The minimum variance estimates of mean larval abundance calculated with this program showed that there was a statistically significant decline in estimated abundance of larvae between 1978 and 1981–1983. Previous, less efficient estimators (e.g., log transformation) were not precise enough to establish this apparent decline statistically.

A review of multispecies patterns of abundance and methods for analyzing community structure of ichthyoplankton assemblages was completed. Co-occurrence because of similar biotic requirements, ecosystem scale, physical processes, or adult community structure does not constitute evidence for interactive relationships among the planktonic larvae. However, most surveys of larval fishes have not been designed specifically to assess interspecific interaction. Multivariate approaches to describing larval fish assemblages and their response to ecological and climatic forcing are necessary. In addition, the problem of sampling variability in studying reef fish recruitment processes was examined. Some aspects of the recruitment problem are intractable with conventional sampling methods because of the cost required to achieve useful precision. Careful formulation of research questions and innovative sampling techniques are needed.

FISHERIES DYNAMICS

Research was concentrated in four areas: (1) population models incorporating the spawning and recruitment patterns of tropical and subtropical species, (2) a growth and claw regeneration model of stone crabs, (3) a model for multigear, size-stratified fisheries, and (4) a model of a population's dynamics associated with bag-limit or allocated-quota controls on fisheries.

The literature on spawning and recruitment patterns of tropical and subtropical fish populations was reviewed, to evaluate the efficacy of current models and analytical techniques. A library of existing microcomputer-based analytical programs was created for testing. Two simulation models incorporating the spawning and recruitment patterns were begun; one is a semicontinuous, age-independent model and the other is a discrete-time model that tracks ages on a short time scale.

Growth data on the Florida stone crab were analyzed. From this analysis, new growth models were created to account for the discontinuous type of growth exhibited by these crustaceans. Estimates of the ages at first maturity, first capture, and terminal molt for male and female crabs were obtained.

The core of a computer model adapted to simulate multi-gear, size-stratified fisheries was completed. The model was first developed in BASIC language, then adapted to FORTRAN to increase speed and memory capacity; it consists of main program and a series of subroutines. Recruitment, growth, and mortality submodels have already been developed, as well as the output and graphing subroutines. The growth submodel was modified a number of times to allow simulation of individual variability within a cohort. Such variability can be adjusted with program inputs, and it results in a simulated population that is length-structured instead of age-structured as in most simulators. This improves the mortality submodel's ability to mimic the fishery operation in which the length of the animal determines its vulnerability to the gear. The mortality submodel simulates the operation of the fleet or fleets and the

change in population numbers due to natural mortality, fishing mortality, and migration. It produces catches by gear and time period as well as population size by length. The output and graphing routines allow the user to control the way the simulator operation is viewed and printed. Research was also conducted on the estimation and revision of some of the inputs used by the model, such as the growth curve and selectivity parameters.

Various probability density distribution models were reviewed for applicability to the bag-limit/allocated-quota problem. The problem stems from a truncation of the distributions caused by those kinds of controls and the evolution of the truncated distributions as the population changes size. The negative binomial and compound negative binomial (or gamma) distributions were selected for the transitional behavior of the moments of the selected probability density distribution models.

TROPICAL ENVIRONMENTAL CHEMISTRY

Environmental chemistry research concentrated on (1) measuring volatile organic compounds and ozone in the tropical environment and (2) identifying the roles of phytoplankton and bacteria in volatile organic compounds.

Preliminary data from the May-June 1984 Radiatively Important Trace Species (RITS) cruise were evaluated. During the cruise volatile organics and ozone were measured synoptically from ship and aircraft between Hawaii and Tahiti along 150°W. The objectives were to determine the relationships between the biosynthesis of volatile reactive organic compounds in the surface ocean and the effect they exert on the proximate distributions of the major oxidants, and radiation absorbers in the boundary layer. Results show that widely varied biogenic volatile organic compounds are produced in the surface ocean and evaporate into the boundary layer. These compounds include saturated and unsaturated hydrocarbons, aromatic hydrocarbons, and compounds containing heteroatoms. Atmospheric concentrations were as high as 275 ppbv for heteroatom compounds at an altitude of 10 m at 10°N. The total concentration of volatile organics and the concentration of ozone reached a minimum at the Equator and, interestingly, the organics present were dominated by aromatic compounds with only traces of the usual array of saturated hydrocarbons.

Tropospheric profiles indicate that highly reactive compounds, such as furan, are rapidly removed within the spray zone, most likely by oxidation processes, whereas the less reactive compounds hexane and toluene are still present at 100 m, though at lower concentrations than those found in the spray zone. It appears that compounds such as acetone and butanone are oxidation products formed in the boundary layer. They exhibit no gradient in relative abundance between 30 and 100 m, yet they are more reactive than hexane and toluene, which do exhibit a pronounced gradient. These preliminary data indicate that the immediate or proximate influence of the volatile organics on the distributions and cycles of the major gaseous species and radicals will be greatest in the lower few hundred meters of the boundary layer.

An improved trace analytical method for dimethylsulfoxide and dimethylsulfone has been developed. The method uses hot, on-column injection, capillary gas chromatography and a sulfur-specific detector. A heated sheath surrounding the inlet of the capillary column eliminates peak splitting and distortion, resulting in greater sensitivity; injecting large sample volumes of polar solvents is also possible. The method also allows for the determination of other polar compounds, such as ethylene glycol, phenol, and octanol in polar solvents. Historically, such determination has been troublesome if not impossible.

Efflux of volatile carbon and sulfur compounds from the surface layer of the oceans is a dominant term of the biologically mediated contribution to atmospheric C, S, and N cycles. The microbial processes of photosynthetic production (phytoplankton) and heterotrophic

decomposition of organic matter (bacteria and fungi) collectively provide the total introduction of organic nutrients into marine ecosystem metabolism. A program was designed to provide several different levels of information about microbial carbon and sulfur metabolism for the RITS mission. Preparations for the August-September cruise to the equatorial Atlantic Ocean included development and testing of new methods for detecting volatiles produced during photosynthesis. Cruise measurements will yield quantitative rates of total input for the upper water column, using direct radioassays of CO_2 and sulfate assimilation.

The photosynthetic component of production will be partitioned into (1) specific biomass synthesis (e.g., protein, carbohydrate, lipid) to provide an index of nutritional status of the phytoplankton, and (2) extracellular release of newly fixed CO_2 as excreted volatile and dissolved organic carbon. A method was developed specifically to trap low-molecular-weight volatile products of photosynthesis on adsorbent columns; the current methods for photosynthesis measurement have no provision for excreted volatile carbon because the removal of ^{14}C-bicarbonate tracer involves vigorous bubbling of the sample. Pre-cruise development indicated that the method was sensitive to 0.5% of total reduced carbon as volatiles. Refined preparation of radioactive bicarbonate stocks has reduced background interference to negligible levels. The partitioning of $^{14}CO_2$ fixation into particulate, dissolved, and volatile components will be made for simulated in situ incubations at six stations during the cruise.

Volatile compounds of known environmental significance include dimethyl sulfide, methyl iodide, and trimethulamine, all of which are products of methionine - catalyzed methylation. Microbial methylamine will be investigated using a variant of the dissolved and volatile excreted material measurement applied to the photosynthesis work described above. Two components of bacterial methylation will be specifically addressed: (1) the proportion of methyl transfers to extracellular products as a quantitative input of one-carbon nonmethane compounds to oceanic surface waters, and (2) specific incorporation of methyl-, sulfur-, and skeletal components of the methionine molecule into cellular polymers and extracellular products as an indication of methionine degradation. The combined results of total microbial sulfate assimilation and bacteria-specific patterns of methionine metabolism may elucidate the bacterial component of oceanic volatile flux.

Plans FY 1986

RECRUITMENT MECHANISMS

Research will continue in three types of ecosystems: pelagic, reef, and estuary.

In the pelagic ocean ecosystem of the bluefin tuna, research will continue by extending the time series of fishery-independent estimates of spawning stock population size as data become available. The extensive existing stock data base of ichthyoplankton, environmental, and satellite information will be scrutinized for correlations among mesoscale oceanographic features and the distribution of spawning and surviving larvae. The preliminary hypothesis to be investigated is that spawning and survival could vary with appropriate oceanic habitat, and that this habitat can be identified by synoptic measurements of variables such as temperature, stratification, and phytoplankton pigment concentration. The heuristic value of these correlations, for predicting the locations of aggregations of adult fishes and for predicting survival of larvae to the recruitment stage, has been augmented by the more specific causal hypotheses generated by the analysis of existing data. A natural extension of this work has been to examine the pelagic habitat of other fishes in the family *Scombridae*, such as the other tunas and mackerels. These fishes are all similar in being fast-swimming schooling predators but they differ in size, seasonal migrations, and preferred distance from shore. They make an

interesting comparative study with regard to requirements for successful spawning, larval survival, and recruitment to their respective fisheries.

Reef fish recruitment will be studied by experimental field work to assess the importance of tidal currents to the apparent periodicity of recruitment from the plankton. Laboratory work to determine the genetic variability of reef fishes in residence at a location and the genetic and age variability of new recruits from the plankton will be initiated to develop a method of detecting whether reef fish populations are self-sustaining or dependent on recruitment from upstream populations.

Field work will begin in Biscayne Bay, a subtropical coastal lagoon estuary, with the objective of assessing the importance of anchovy in the trophic dynamics of the fish community. Although it was the most abundant species found in an ichthyoplankton study, and may be an important consumer of plankton, there is no directed fishery for anchovy and it was not sampled adequately in a recent trawl survey. An understanding of the fishery ecosystem of Biscayne Bay requires more knowledge about this abundant forage fish, which is a trophic link to plankton production.

Other field work in Biscayne Bay will study the recruitment of fishes to man-made structures, with the objectives of describing seasonal patterns of species composition and abundance and comparing these patterns with those occurring on natural hard-bottom facies in the Bay.

FISHERIES DYNAMICS

Research into the use of decision analysis will be expanded. In particular, the feasibility of using "expert systems" in fishery dynamics will be investigated. Expert systems are interactive computer programs that use techniques of the science of artificial intelligence to solve problems. They are applicable wherever a decision-making problem can be defined to a computer. Expert systems make the knowledge and logical processes of an expert or group of experts available to many others, freeing the experts to work on innovation or unsolved problems. Expert systems use data, logical inference, probabilities, and analytical models to recommend a solution to a problem and to explain the basis for the recommendation. Most other analytical decision support tools merely condense the data, which then require expert interpretation.

Modeling work involving spawning and recruitment patterns, the stone crab life history, and bag limits will be continued. The optimization submodule of the multigear size-stratified model will be completed and the whole model tuned with data from several fisheries, possibly the Moroccan hake fishery and Gulf of Mexico king mackerel fishery.

TROPICAL ENVIRONMENTAL CHEMISTRY

Continued research within the RITS program includes two planned cruises: one during August-September 1986 in the tropical Atlantic Ocean and the other during May-June 1987 in the equatorial Pacific Ocean. Both cruises will concentrate on advancing our understanding of the geochemical cycles and distribution of major constituents of the troposphere. Volatile organics, nonmethane hydrocarbons, methane, ozone, and carbon monoxide will be measured. Vertical profiles within the boundary layer for volatile organics and ozone will be obtained by use of a tethered balloon. Samples of volatile organics will be analyzed.

Refinement of the volatile trapping method for methylated excretion products of bacterial metabolism and examination of environmental perturbations stimulating methylation activity can be accomplished by a series of culture experiments using marine bacterial isolates. Work related to the uptake of methionine from extremely dilute solution and its patterns of metabolism will provide the focus for these and related studies.

JISAO

The Joint Institute for Study of the Atmosphere and Ocean (JISAO) was formed in FY 1977 with the University of Washington. The main areas of emphasis within JISAO continue to be climate dynamics, estuarine processes, environmental chemistry, and interannual variability of fisheries recruitment. JISAO climate research has been organized around two main themes: large-scale atmosphere-ocean interaction in the tropics and planetary-wave/mean-flow interaction. The existence of the JISAO program has substantially increased the level of activity in these areas on the University campus, and it has served to promote collaboration between PMEL scientists and University scientists. It has also resulted in increased interaction between atmospheric scientists and physical oceanographers on the University faculty.

Accomplishments FY 1986

JISAO contributed to the EPOCS and TOGA programs through the support of four postdoctoral appointees and seven visiting scientists, whose research has involved both observational and theoretical studies. These research activities took place:

- Study of two fundamental problems of large-scale dynamics: (1) the linear theory of tropospheric stationary waves, and how it pertains to the pattern of quasi-stationary waves observed in middle latitudes during winter; (2) the nature of nonlinear flows in a two-layer model.

- Diagnosis of observations and model data on the properties of retrograding low-frequency disturbances over the North Pacific Ocean, and experiments with the NCAR (National Center for Atmospheric Research) Community Climate Model to study the sensitivity of the time evolution of the circulation to the presence of synoptic-scale disturbances in the initial conditions.

- Use of near-surface pressure sensors in the Galápagos Islands and current measurements at 0°S, 95°W to investigate the time variability and spatial structure of fluctuations in the 50- to 10-day frequency bands.

- Modeling of the current response to a spectral wind forcing, to investigate coastal current response to an analytical form of the wind stress wavenumber spectrum.

JISAO sponsored a 1-week workshop on the theory of the oceanic general circulation, which provided a unique opportunity for an informal exchange of ideas between scientists from different countries, working on a variety of research topics relevant to the ocean circulation.

Scientific activity at the Experimental Climate Forecast Center focused on the preparation of a reformatted version of the National Meteorological Center (NMC) twice-daily gridpoint data from 1962 onward, which will be made available in an optical disk format to research groups throughout the country through the NCAR Data Library.

Plans FY 1987

- Continue an active program in climate research. Four postdoctoral appointees and a senior visiting scientist will be in residence, and short-term visitors will give seminars.

- Receive visits from two senior scientists during spring and summer 1987 under the Institute Distinguished Scientist Program initiated last year.

- Hire a director for the Environmental Climate Forecast Center.
- Increase JISAO involvement in fisheries-oceanography research.

JIMAR

The Joint Institute for Marine and Atmospheric Research (JIMAR) is located at the University of Hawaii. JIMAR was formed in FY 1978 in association with the University and PMEL. The principal research interests of JIMAR are equatorial oceanography, climate, and tsunamis.

Accomplishments FY 1986

EQUATORIAL OCEANOGRAPHY

The Pegasus velocity profile data taken during the Pacific Equatorial Ocean Dynamics (PEQUOD) program was analyzed and a manuscript on deep zonal currents in the central equatorial Pacific was completed. The relationship between near-surface shear and surface wind stress is being studied using the Pegasus profiles, to investigate the relationship between eddy viscosity and stress near the Equator.

The second U.S.-Australia Western Equatorial Pacific Ocean Circulation Study (WEPOCS) expedition took place in January and February 1986 during which Pegasus profiles were obtained between 1°S and 2°N in the western Pacific at 150°E. These show evidence for a strong annual cycle at the Equator between the surface and 1500 m depth. Acoustic Doppler profiles of upper ocean currents were also recorded with the RDI instrument on the *Moana Wave*.

A hydrographic survey in the near-equatorial region northeast of Papua, New Guinea, was completed; the observations will be compared with similar observations obtained during WEPOCS I in June–August 1985. The pressure gauges deployed in WEPOCS I were recovered. Major WEPOCS results to date include the discovery of a New Guinea coastal undercurrent and the confirmation of Tsuchiya's hypothesis that waters of the equatorial undercurrent come primarily from the Southern Hemisphere.

The Line Islands work continued for the second year, including pressure gauge observations, hydrography, and Inverted Echo Sounder (IES) deployments. The IES work is being done jointly with the University of Rhode Island. Both the IES and pressure gauge records showed energetic 30-day oscillations during the fall of 1985, weakening after the beginning of 1986. These oscillations and their seasonal and interannual variability are the main focus of this work.

The Pacific Sea Level network continues to operate; 14 island stations and 5 South American coastal stations now report via satellite. These stations are useful for tsunami warnings and for monitoring low-frequency sea level variations. Sea level pulses associated with westerly-wind events in the western Pacific were monitored. A pulse of 12-cm amplitude and 10-day duration was generated in May and observed at Tarawa and subsequently at Christmas Island and the Galápagos.

A TOGA Sea Level Center was established; it maintains a file of daily sea level values from 90 stations in the tropical Pacific and Indian Oceans. Monthly maps of Pacific sea level are prepared and issued as part of an Integrated Global Ocean Station System (IGOSS) pilot project. New gauges are being installed to implement a sea level network in the tropical Indian Ocean.

A model for generation of Yanai waves in the Indian Ocean forced by zonal winds and the effect of coastline geometry is being worked on as well as a modeling study of sea level variability along the eastern boundary of the Pacific.

In December 1985 JIMAR assisted in hosting the visit to Honolulu of the R/V *Xianyonghong 14*, during the first phase of the U.S.–People's Republic of China field work.

CLIMATE

The principal EPOCS-funded research is the investigation of the tropical cyclones as triggers and/or responses to the ENSO cycle. A relationship between the occurrence of off-season storms and major ENSO events was documented and tested by the forecast of a 1986 El Niño. Although a twin cyclone event in May generated a significant equatorial Kelvin wave, further evolution suggested by the hypotheses has not materialized.

A synoptic climatology of the near-equatorial trough (a precursor to cyclogenesis) was developed from 15 years of serial analyses supplemented by COADS ship winds. The data suggest that long-period (40–60 day) tropospheric oscillations are related to off-season trough formation and cyclogenesis. It was also found that major cold surges in the Asian winter monsoon can, under proper circumstances, cause westerly wind events in the equatorial west Pacific. We have isolated such an event, which coincided with development of tropical storm Kathy in January 1976. Kathy carried 20-kn westerlies along the Equator.

Using the COADS, a method was developed and evaluated for computing tropical wind stress from monthly mean winds. The method shows that the correction factor required to produce monthly stress from monthly mean winds, in lieu of individual observations, is a function of the wind variance. The correction factors have been determined for the tropics and our monthly mean winds data set for the Pacific beginning from January 1979 has been converted to monthly stress and made available to ocean modelers.

The surface wind and new stress data base continues in production. The 1985 subjective analysis was extended to include the Indian and Atlantic Ocean.

TSUNAMIS

Final design and fabrication of five coastal tsunami gauges was completed. Four of the gauges were deployed when, on May 7, an earthquake occurred at Adak and generated a tsunami. Two gauges produced data.

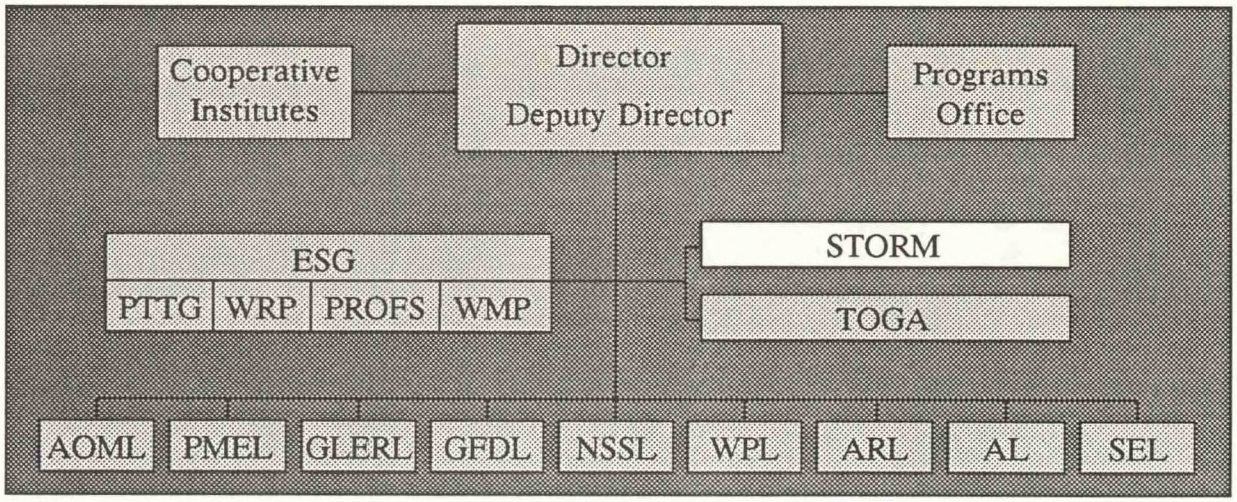
Plans FY 1987

EQUATORIAL OCEANOGRAPHY

- Conduct the third Line Islands cruise.
- Continue operation of the Pacific Sea Level Network and convert three additional stations to satellite transmission. Continue analysis of the data with emphasis on a detailed evaluation of the response of sea level during the last El Niño event, on the water exchange between the Pacific and Indian Ocean, and on the development of 30–50 day waves.
- Establish new sea level stations at Diego Garcia, in the Maldive Islands, and on Maritius; make progress in negotations for stations in Indonesia.

CLIMATE

- Continue the studies of tropical cyclones as ENSO components emphasizing interannual and intraseasonal variations in storms and precursor near-equatorial troughs.
- Publish a climatological atlas for each ocean, containing analyzed maps of wind direction, wind speed, wind stress, sea-surface temperature, and sea level pressure.
- Continue production of monthly mean data sets and increase the interaction with ocean and atmospheric modelers.



STORM PROGRAM OFFICE
Boulder, Colorado
William H. Hooke, Director

The National Stormscale Operational and Research Meteorology (STORM) Program Office was established in NOAA in November 1984. The office is funded by and serves the Federal agencies expected to participate in the program. It receives general guidance from the Subcommittee on Atmospheric Research (SAR) of the Federal Coordinating Committee for Science, Engineering, and Technology. It receives administrative support from the Environmental Research Laboratories of NOAA. The STORM Program Office acts as the inter-agency focal point for all STORM-related activities and, following full implementation of the program, will coordinate field research and the interface with participating operational components.

STORM GOALS AND RELATED ACTIVITIES

The STORM Program will address fundamental mesoscale weather problems that pose a significant scientific challenge and are of major concern to the economic well-being of the nation and the safety of its citizens. Specifically the National STORM Program has two goals:

- To enable meteorologists, public and private, to observe and predict the occurrence of small-scale weather phenomena with substantially improved timeliness and accuracy.

- To apply improved predictive capability to the tasks of protecting the public, serving the national economy, and meeting defense requirements.

Designed to build upon the operational and research strengths of Federal agencies, universities, and private groups, the program works with participating institutions to define roles and activities that are compatible with their goals and objectives, and at the same time are essential to the broader national STORM program.

To accomplish its mission NOAA has invested heavily in observing and data management systems that will improve short-range severe weather warnings. While doing this, NOAA is creating an unprecedented high-resolution operational weather-observing system and data base of enormous potential

scientific value. NOAA's mission also includes a strong research component, since improved fundamental understanding of atmospheric processes is absolutely essential to improved weather services. Using the operational data sets of the future as well as special research programs, NOAA scientists will carry out a strong program of basic research that will make possible more accurate and specific forecasts in the critical 1-hour to 1-day period. Thus, one of NOAA's primary missions—the collection and management of high-quality meteorological data for operations and research—is also essential to STORM, and is a natural role for NOAA in this important national program.

Similar compatibility exists between NASA's mission to develop advanced geophysical sensors on the one hand and the general need to observe storms in even greater detail over larger areas on the other. The basic research missions of NSF and universities are also compatible with the STORM goals. NCAR's strong Atmospheric Technology Division (ATD) and Convective Storms Division (CSD) are in a position to lead many of the various field experiments that can be nested within NOAA's high-resolution operational data system. NCAR's Atmospheric Analysis and Prediction Division and CSD will also contribute to important STORM modeling efforts. Other Federal agencies and groups such as DOI, DOE, DOD, and EPA address specific mesoscale meteorological issues that are also compatible with this national theme and can be solved within the context of the STORM Program.

Translation of basic research results into operationally effective forecast techniques is a core mission of ERL's meteorological Laboratories. This effort spans a range of activities from specific case studies to the use of advanced computer systems to assimilate, model, and display mesoscale weather. ERL's role as the essential interface between basic research and the results from many field experiments, and the operational forecast offices of NWS, is clearly defined in the STORM Program. Here too the program will break new ground with the implementation of experimental forecast centers, where operational and research meteorologists will work side-by-side to provide one of NOAA's most important services, mesoscale weather predictions.

Accomplishments FY 1986

The initial framework for a national STORM Program was prepared in 1982. The program design for STORM-Central was prepared in 1984 and endorsed by the National Academy of Sciences. Those two concepts now form the basis of a STORM implementation plan. A strategy to accomplish the original scale-interaction research and improvement of mesoscale service goals has been developed. It calls for the exploitation of the coming higher-resolution operational data sets, coupled with smaller specific field experiments when additional data are required, to conduct a broad range of mesoscale and scale-interaction research. The timing of specific STORM experiments will depend upon the installation schedules for new sensors such as NEXRAD, Doppler radar, automatic wind and thermodynamic Profilers, and advanced satellite systems. The focus of such experiments will be national rather than regional.

This broad strategy includes specific tactics:

- Development of advanced data assimilation methods for analysis and numerical model initialization.
- Acceleration of mesoscale numerical model research and application.
- Conduct of specific field experiments that exploit the high-resolution operational data sets and thus require fewer resources to implement.
- Creation of advanced data archive and retrieval systems that will speed researcher access to the wealth of new data.

This strategy was articulated in briefings to the agencies and groups interested in the STORM Program. These briefings led to the drafting of new initiatives in NOAA and NSF to fund the portions of the program that relate to each agency's specific mission and role in the STORM Program.

The STORM working groups were charged with developing the experimental hypothesis and specific requirements for conducting STORM-related research. This effort will provide the scientific input for the implementation plan.

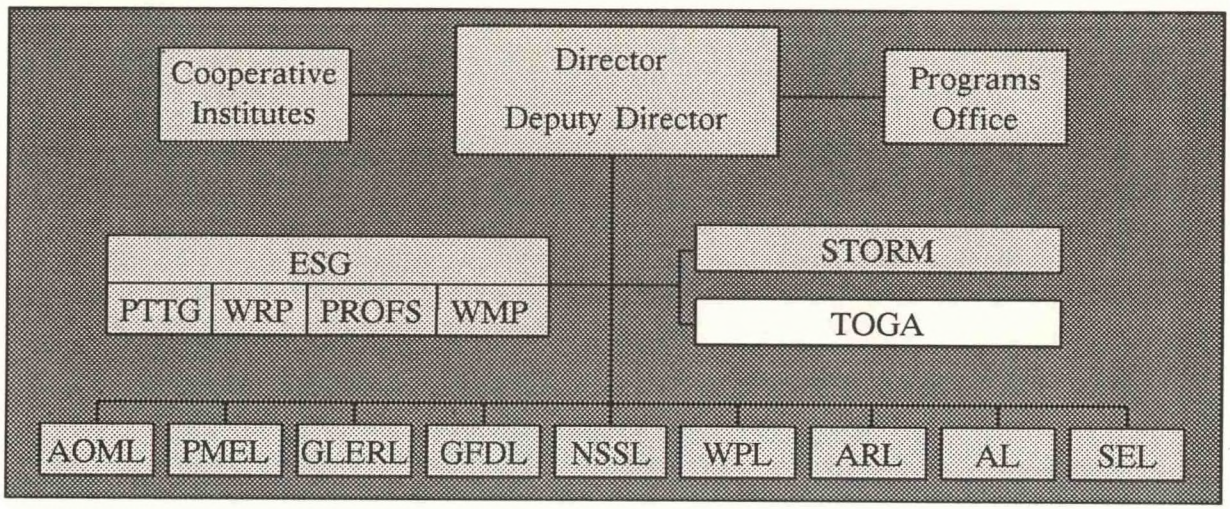
Plans FY 1987

The implementation plan will be completed and made available to STORM participants for use in developing specific initiatives compatible with the main program.

The original funding initiatives will be updated where necessary and submitted to the budget process.

Links will be established with other projects that are relevant to STORM, and necessary coordination will begin. These projects include various planned field experiments; the NEXRAD, Profiler, and other new sensor projects; the advanced data management projects being implemented by NWS and other agencies; and projects such as the NWS Modernization And Restructuring Demonstration (MARD).

The design of STORM data management systems such as a mesoscale archive and forecaster researcher workstations will begin. These systems will be built as funds become available.



INTERNATIONAL TOGA PROJECT OFFICE

Boulder, Colorado

Jimmy A. Lyons, Acting Director

The International Tropical Ocean and Global Atmosphere (TOGA) Project Office (ITPO) supports the ongoing planning as well as the international coordination of activities contributing to the International TOGA program. The Project Office receives its general guidance from the Director, World Climate Research Programme (WCRP) and operates as a component of the Joint Planning Staff of the World Meteorological Organization (WMO) headquartered in Geneva, Switzerland. ITPO is a contribution by the United States to International TOGA and receives its administrative support from the Environmental Research Laboratories of NOAA.

The scientific aspects of TOGA have been defined and planned by the International TOGA Scientific Steering Group (SSG). The TOGA SSG was established by the Joint Scientific Committee and the Committee on Climatic Changes on the Ocean. The Joint Scientific Committee (JSC) was created by WMO and the International Council of Scientific Unions (ICSU); the Committee on Climatic Changes and the Ocean (CCCO) was formed by the Intergovernmental Oceanographic Commission (IOC) and the Scientific Committee on Oceanic Research (SCOR). The SSG also formulates scientific priorities for the implementation of TOGA.

ITPO is the primary office for initiating formal international correspondence and for carrying out international liaisons at the working level, as required for the implementation or further development of TOGA observing or data systems. Other activities include the following:

- Prepare and update, on an annual basis, the detailed implementation and/or operations plans for the program.
- Ensure the timely flow of operational and other relevant information to TOGA participants and members of the JSC, CCCO, and TOGA SSG.
- Prepare documentation concerning the international coordination of TOGA projects.
- Provide secretarial support to the International TOGA SSG.

TOGA CLIMATE RESEARCH

Research on large-scale oscillations of the tropical atmosphere has been conducted for more than 80 years. Through the years, scientists correlated these low-frequency atmospheric oscillations with changes occurring in the tropical oceans. Later, it was realized that these interactions between the tropical oceans and atmosphere were linked to changes of weather and climate in the higher latitudes of both hemispheres. However, it is only recently that the latest analyses of data and results from field experiments and theoretical work have come together to create a sense of priority in the scientific community concerning this subject.

In the last few years, recognition of the importance of predicting variations in the Earth's climate has led to a large increase in individual research investigations. However, it is clear that progress in understanding and predicting these climate events will require information about the relevant atmospheric and oceanic variables. TOGA is an international activity organized to provide this information. TOGA is part of the World Climate Research Programme established by WMO and ICSU to determine to what extent climate can be predicted and the extent of human influence on climate. The TOGA program was organized with the joint support of ICSU's Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission of UNESCO.

The scientific community has been aware of the existence of anomalous oceanic and atmospheric circulation patterns that develop on time scales of several months to several years, and has recognized that a significant part of these variations can be explained by the dynamics of the coupled system consisting of the tropical oceans and the global atmosphere. The study of this system is the objective of the TOGA program.

New insights have been gained on the planetary-scale monsoon system under the Monsoon Experiment (MONEX) Sub-programme of the First GARP Global Experiment (FGGE), as well as under national, bilateral, and international monsoon research programs prior to MONEX. The subseasonal and interannual variability of monsoons is now regarded as having close links with ocean surface conditions on regional and planetary scales. Monsoon variability is also a function of interactions with other major atmospheric systems. Recognizing the importance of planetary-scale monsoons as an energy source for the global atmosphere and as a potential link to Southern Oscillation and El Niño events, the TOGA program has included the study of monsoon variability as an element in achieving its overall objectives.

Accomplishments FY 1986

The first edition of the International TOGA Implementation Plan was published by ITPO in October 1985. Almost 500 copies were distributed to participating organizations and individuals in more than 100 countries. The first draft of the second edition of the Plan was prepared and distributed to the TOGA SSG and other concerned individuals. The TOGA Implementation Plan was designed in a loose-leaf format in order to facilitate changes and updates during the 10-year life of the TOGA program.

Two sessions of the International TOGA SSG were held, the first on 10–14 February 1986 in New Delhi, India, and the second on 1–5 September in Abingdon (Oxford) England. Both sessions reviewed in detail the status of implementation of TOGA as well as the state of the scientific plan. The ITPO provided administrative support and both sessions were attended by the Acting Director.

Four issues of TOGA TOPICS, the quarterly newsletter of the ITPO, were published. The quality of the newsletter was greatly improved during the course of the fiscal year. TOGA TOPICS is now distributed to 650 individuals in 117 countries, and block distributions are made to WMO, IOC, the U.S. TOGA Office, and the World Ocean Circulation Experiment (WOCE) Planning Office. Arrangements were made to combine the publication of TOGA TOPICS with the Tropical Ocean-Atmosphere Newsletter (TO–AN) beginning with the January 1987 issue. The combined newsletters will represent a

major means of distributing information concerning TOGA and recent research relating to the tropical oceans and global atmosphere to interested persons throughout the world. It is anticipated that the combined newsletters will be circulated to about 1500 scientists and administrators in well over 100 countries. TOGA TOPICS as included in the TO-AN will be considered a United States contribution to the WCRP and International TOGA.

The International TOGA Film Library has continued to operate, and efforts were begun to obtain new titles and also to provide films on video tape in the major global television standards.

Printing and distribution of the TOGA brochure were completed. More than 10,000 brochures in English, French, Spanish, and Russian were printed and distributed either directly by the ITPO or through the WMO, IOC, or U.S. TOGA Office. In addition, versions in Japanese and Chinese were printed in Japan and China, using full color composites provided by the Project Office.

Major efforts were undertaken to encourage the establishment of the TOGA Sea Level and XBT Networks. Significant enhancement of the Sea Level Network has been achieved in the Pacific Ocean, where the network is nearing completion, and in the Indian Ocean. The TOGA XBT Networks in both the Pacific and Atlantic have been greatly strengthened and several new lines have been initiated in the tropical Indian Ocean.

The TOGA Tropical Sea Level Data Centre was established at the University of Hawaii. In addition, terms of reference for the TOGA Tropical Ocean Sub-surface Data Centre were developed and provided to the WMO and IOC for action. A Member State has been officially requested to undertake the operation of this Centre and a positive reply is expected shortly.

The first part of an ITPO Automated Management System (AMS) was implemented. The ITPO AMS is a PC-based system that will track the status of implementation of the TOGA observing and data systems. The AMS is being implemented on the XBT and Sea Level Networks and will be expanded to the other parts of the observing and data systems as required, and as the system is developed.

The ITPO provided administrative and secretarial support to the First Informal Planning Meeting on the WCRP in Geneva on 12-16 May 1986. Representatives of 24 countries attended. It was determined that considerable interest in and support for TOGA exists at the intergovernmental level. New commitments were made by National Delegates in support of various portions of the TOGA Observing and Data Systems. Also, approval was expressed for the WCRP and TOGA scientific concepts and implementation plans.

The United States offered to provide financial and material support, as well as the services of two professional personnel, in order to re-establish the ITPO outside this country. This offer was made contingent upon a matching offer by at least one other country to second a professional and one country or organization to provide appropriate office space/facilities and secretarial support. Arrangements are under way to consummate this offer, and it is anticipated that the Project Office will be relocated during the second half of FY 1987.

Plans FY 1987

- Complete the second edition of the TOGA Implementation Plan and distribute.
- Prepare ITPO to be physically and administratively relocated during the third quarter of FY 1987.
- Incorporate TOGA TOPICS into the Tropical Ocean-Atmosphere Newsletter. The TOGA TOPICS portion will continue to be collected and edited by the ITPO and will be provided as a complete section for inclusion within the TO-AN.
- Make several missions to countries participating or considering participating in International TOGA:

  - To rectify data exchange problems.
  - To encourage increased participation.
  - To make presentations.
  - To gather information.
  - To provide information or instruction on TOGA observational and/or data systems.

- Continue development of ITPO Automated Management System.

- Provide secretarial support to the sixth session of the TOGA SSG and to the first meeting of the TOGA SSG Officers.

- Prepare documentation for relevant JSC, CCCO, WMO, and IOC meetings.

- Send letters and material to various countries, institutions, organizations, and individuals concerning participation in TOGA.

APPENDIX: Acronyms and Initialisms

ACC	Alaska Coastal Current
ACM	acoustic current meter
ACURATE	Atlantic Coastal Unique Regional Atmospheric Tracer Experiment
ADAM	AOML Data Assimilation Model
ADCP	acoustic Doppler current profiler
AE	Atmosphere Explorer
AFE	average forecast errors
AFOS	Automation of Field Operations and Services (NWS)
AGASP	Arctic Gas and Aerosol Sampling Program
AI	artificial intelligence
AIMCS	Airborne Investigations of Mesoscale Convective Systems
AL	Aeronomy Laboratory (ERL)
ALPEX	Alpine Experiment
ANATEX	Across North America Tracer Experiment
ANL	Argonne National Laboratory
AOML	Atlantic Oceanographic and Meteorological Laboratory (ERL)
APEX	Arctic Polynya Experiment
ARL	Air Resources Laboratory (ERL)
ARTCC	Air Route Traffic Control Center
ASCOT	Atmospheric Studies in Complex Terrain (DOE)
ATD	Atmospheric Transport and Diffusion [model]
ATDD	Atmospheric Turbulence and Diffusion Division (ARL)
ATLAS	Automated Temperature Line Acquisition System
AVHRR	Advanced Very-High-Resolution Radiometer
AWIPS–90	Advanced Weather Interactive Processing System for the 1990s
AWS	Air Weather Service (USAF)
AXCP	airborne expendable current probe
BAO	Boulder Atmospheric Observatory (ERL)
BPR	bottom pressure recorder
CAC	Climate Analysis Center (NWS/NMC)
CAMS	control and monitoring system
CAPTEX	Cross-Appalachian Tracer Experiment
CCM	Community Climate Model
CDIC	Carbon Dioxide Information Center
CEORS	Center for Earth Observations and Remote Sensing (CIRES)
CG	cloud to ground
CHILL	Chicago – University of Illinois [radar system]
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIPER	climatology/persistence [model]
CMR	Compressed Marine Reports
CN	condensation nucleus
COADS	Comprehensive Ocean-Atmosphere Data Set

CODAR	Coastal Ocean Dynamics Applications Radar
COE	Corps of Engineers (U.S. Army)
COHMEX	Cooperative Huntsville Meteorological Experiment
COMEDS	Continental U.S. Meteorological Data System
COMMA	Central Oklahoma Mesoscale Modeling and Analysis
CONDORS	Convective Diffusion Observed by Remote Sensors
COSPAR	Committee for Space Research (ICSU)
CRP	Climate Research Project (ERL/ESG)
CRT	cathode-ray tube
CSU	Colorado State University
CTD	conductivity, temperature, depth
CTDM	Complex Terrain Dispersion Model
CURTAIN	Central U.S. RADM Test and Assessment Incentives
CWP	Central Weather Processor (FAA)
DAR^{3}E	Denver AWIPS–90 Risk Reduction and Requirements Evaluation (FAA)
DLM	deep-layer mean
DMS	dimethyl sulfide
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DOE	Department of Energy
DOM	dissolved organic material
DOPLIGHT	Doppler-Lightning
DOPLOON	Doppler-balloon
DRASER	Doppler Radar and Storm Electricity Research (NSSL)
ECC	electrochemical concentration cell
EC–GC	electron capture gas chromatography
ENSO	El Niño/Southern Oscillation
EOF	empirical orthogonal function
EPA	Environmental Protection Agency
EPOCS	Equatorial Pacific Ocean Climate Studies
EPS	energy particle sensor
ERKE	excess rotational kinetic energy
ERL	Environmental Research Laboratories (NOAA)
ESG	Environmental Sciences Group (ERL)
EUV	extreme ultraviolet
FAA	Federal Aviation Administration
FACTS	Florida Atlantic Coast Transport Study
FASINEX	Frontal Air-Sea Interaction Experiment
FGGE	First GARP Global Experiment
FIRE	First ISCCP Regional Experiment
FM–CW	frequency modulation–continuous wave
FOCI	Fisheries Oceanography Coordinated Investigations (NOAA)
FOX	Fishery Oceanography Experiment
FT–IR	Fourier transform infrared
FTS	Fourier transform spectrometer
GAGE	Global Atmospheric Gas Experiment

GALE	Genesis of Atlantic Lows Experiment
GARP	Global Atmospheric Research Program
GC	gas chromatography
GCM	general circulation model
GCM	Global Climate Monitoring
GDAS	GOES Data Acquisition System
GFDL	Geophysical Fluid Dynamics Laboratory (ERL)
GLERL	Great Lakes Environmental Research Laboratory (ERL)
GMCC	Geophysical Monitoring for Climatic Change (ARL)
GOES	Geostationary Operational Environmental Satellite
GPI	GOES Precipitation Index
GSFC	Goddard Space Flight Center (NASA)
GTS	Global Telecommunication System
GWMF	gravity wave momentum flux
HF	high frequency
HLMS	High-Latitude Monitoring Station
HRC	highly reflective clouds
HSC	hierarchical storage controller
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
IES/PG	inverted echo sounder/pressure gauge
IGM	Interplanetary Global Model
IGOSS	Integrated Global Ocean Station System
INEL	Idaho National Engineering Laboratory
INPUFF	integrated puff [model]
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPA	Intergovernmental Personnel Act
ISCCP	International Satellite Cloud Climatology Project
ISDME	International Sulfur Deposition Model Evaluation
ITPO	International TOGA Project Office
IUWDS	International Ursigram and World Days Service
JIC	Joint Ice Center (Navy-NOAA)
JIMAR	Joint Institute for Marine and Atmospheric Research
JISAO	Joint Institute for Study of the Atmosphere and Ocean
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LGM	last glacial maximum
LIMS	Limb Infrared Monitor of the Stratosphere
LMR	laser magnetic resonance
LORAN	long-range aid to navigation
L-RERP	Long-Range Effects Research Program
LTE	local thermodynamic equilibrium
MAP	Middle Atmosphere Program (SEL)

MAPS	Mesoscale Analysis and Prediction System (PROFS)
MARD	Modernization and Restructuring Demonstration (NWS)
MCC	mesoscale convective complex
MCS	mesoscale convective system
MEPED	Medium Energy Proton and Electron Detector
METREX	Metropolitan Tracer Experiment
MFM	movable fine-mesh [hurricane model]
MHD	magnetohydrodynamic
MIZEX	Marginal Ice Zone Experiment
MONEX	Monsoon Experiment (FGGE)
MPBL	marine planetary boundary layer
MST	mesosphere-stratosphere-troposphere
MVVP	modified velocity volume processing
NAPAP	National Acid Precipitation Assessment Program
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NCAR	National Center for Atmospheric Research
NECC	North Equatorial Countercurrent
NEPRF	Naval Environmental Prediction Research Facility
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NEXRAD	Next-generation weather Radar
NHC	National Hurricane Center (NWS)
NICG	National Interagency Coordinating Group
NMC	National Meteorological Center (NWS)
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOMAD	Navy Oceanographic Meteorological Automatic Device
NORPAX	North Pacific Experiment
NOS	National Ocean Service
NOZE	National Ozone Expedition
NRC	National Research Council
NRC	Nuclear Regulatory Comission
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NSSL	National Severe Storms Laboratory (ERL)
NWAFC	Northwest and Alaska Fishery Center
NWP	numerical weather prediction
NWRI	National Water Research Institute (Canada)
NWS	National Weather Service (NOAA)
OAR	[Office of] Oceanic and Atmospheric Research (NOAA)
ODW	Omega dropwindsonde
OLR	outgoing longwave radiation
PACE	Precipitation Augmentation for Crops Experiment
PAH	polycyclic aromatic hydrocarbon
PAM	portable automated mesonetwork
PAN	peroxyacetyl nitrate

PBL	planetary boundary layer
PEQUOD	Pacific Equatorial Ocean Dynamics
PMEL	Pacific Marine Environmental Laboratory (ERL)
POWER	PROFS Operational Weather Education and Research
PRECP	Processing of Emissions by Clouds and Precipitation
PRE-STORM	Preliminary Regional Experiment for STORM-Central
PROFS	Program for Regional Observing and Forecasting Services (ERL/ESG)
PSD	prevent significant deterioration
PTTG	Profiler Technology Transfer Group
QSTING	quasi-spectral time integration on nested grids
RADM	Regional Acid Deposition Model
RAFS	Regional Analysis and Forecast System
RELMAP	Regional Lagrangian Model of Air Pollution
RFP	request for proposals
RGON	Remote Geophysical Observing Network
RITS	Radiatively Important Trace Species
ROM	Regional Oxidant Model
RRSD	Research Rapid-Scan Data
RSMAS	Rosenstiel School of Marine and Atmospheric Sciences (U. of Miami)
RSTN	Radio Solar Telescope Network
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stationary Automated Mesonetwork
SANBAR	Sander's Barotropic [model]
SAO	surface aviation observation
SAR	Subcommittee of Atmospheric Research (STORM)
SBUV	solar backscatter ultraviolet
SCCCAMP	South Central Coast Cooperative Aerometric Monitoring Program
SCOR	Scientific Committee on Oceanic Research (ICSU)
SCOSTEP	Scientific Committee for Solar-Terrestrial Physics
SCR	surface contour radar
SDHS	Satellite Data Handling System
SEC	South Equatorial Current
SEL	Space Environment Laboratory (ERL)
SELDADS	SEL Data Acquisition and Display System
SELSIS	SEL Solar Imaging System
SEM	Space Environment Monitor
SESC	Space Environment Services Center (SEL)
SFMR	stepped-frequency microwave radiometer
SLAR	side-looking airborne radar
SLEUTH	System for Locating Eruptive Underwater Turbidity and Hydrography
SLP	sea level pressure
SME	Solar Mesosphere Explorer
SO	Southern Oscillation
SOON	Solar Observing Optical Network
SPACE	Satellite Precipitation and Cloud Experiment
SSG	Scientific Steering Group (TOGA)
SSMR	Scanning Multifrequency Microwave Radiometer

SST	sea-surface temperature
STACS	Subtropical Atlantic Climate Studies
STIP	Study of Traveling Interplanetary Phenomena
STORM	Stormscale Operational and Research Meteorology
SXI	Solar X-ray Imager
TAG	Trans–Atlantic Geotraverse
TED	Total Energy Detector
THEO	Theophrastus [expert system]
THRUST	Tsunami Hazard Reduction Using System Technology
TIROS	Television and Infrared Observation Satellite
TMO	Table Mountain Observatory
TOGA	Tropical Oceans and Global Atmosphere
TOPEX	Topographic Experiment
TOTO	Totable Tornado Observatory
TOVS	TIROS–N Operational Vertical Sounder
TRM	total reactive manganese
TTO	Transient Tracers in the Ocean
UGLCCS	Upper Great Lakes Connecting Channels Study
UHF	ultrahigh frequency
USAF	U.S. Air Force
USGS	U.S. Geological Survey
UV	ultraviolet
VAS	VISSR Atmospheric Sounder
VENTEX	Venting Experiment
VHF	very high frequency
VISSR	Visible and Infrared Spin-Scan Radiometer
VLF	very low frequency
WATOX	Western Atlantic Ocean Experiment
WAVEDISS	Wave Attenuation, Variability, and Energy Dissipation In Shallow Seas
WCRP	World Climate Research Programme (WMO–ICSU)
WDC	World Data Center
WEPOCS	Western Equatorial Pacific Ocean Circulation Study
WINE	Winter in Northern Europe
WMO	World Meteorological Organization
WMP	Weather Modification Program (ERL/ESG)
WOCE	World Ocean Circulation Experiment
WPL	Wave Propagation Laboratory (ERL)
WRP	Weather Research Program (ERL/ESG)
WSFO	Weather Service Forecast Office
WWCE	westerly wind/convection episode
XRS	X-Ray Sensor

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