HURRICANE RESEARCH DIVISION

FISCAL YEAR 1988 PROGRAMS - FISCAL YEAR 1989 PROJECTIONS

Staff, Hurricane Research Division

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
January 1989

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
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OVERVIEW

HURRICANE RESEARCH DIVISION

ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORY

FY-88 PROGRAMS - FY-89 PROJECTIONS

INTRODUCTION

The Hurricane Research Division (HRD) is NOAA's primary focus for research on hurricanes and tropical meteorology. HRD's research is directed at improved hurricane prediction through improved physical understanding of the structure and dynamics of these storms. HRD makes use of the NOAA P-3 research aircraft to acquire data sets that are analyzed to obtain a better understanding of the dynamics and energetics of the hurricane's inner core. Observational studies of the hurricane's synoptic environment are conducted, as are theoretical and numerical modeling studies of the hurricane.

HRD interacts with the National Hurricane Center (NHC) in all phases of its research, with the National Meteorological Center (NMC) and the Geophysical Fluid Dynamics Laboratory in research concerned with numerical modeling of hurricanes and with the National Severe Storms Laboratory (NSSL) in the study of landfalling hurricanes. HRD cooperates with the National Center for Atmospheric Research (NCAR) on problems related to hurricane rainbands. Cooperative research with other NOAA groups, Federal agencies, private sector groups, and universities is also in progress.

Over the last few decades, there has been considerable improvement in our understanding of hurricanes and in our ability to simulate them with numerical models. However, more work needs to be done before we are able to forecast hurricane tracks and changes in hurricane intensity with an acceptable degree of accuracy. During the past fiscal year, Atlantic Tropical Storms and/or Hurricanes Floyd (October 1987), Florence (September 1988), and Gilbert (September 1988) provided a substantial body of data to support these research efforts.

On October 10 and 11, 1987, HRD conducted synoptic-flow experiments on the periphery of Tropical Storm Floyd. At this time, Floyd's strongest winds, measured at 500 m, were 20 to 25 m s^{-1} and the minimum surface pressure was $\sim$ 998 mb. On both days, the mandatory pressure-level information from the Omega dropwindsondes (ODW's) was transmitted in real time to NHC and NMC.

HRD's ODW experiments are coordinated with NMC, the Space Science and Engineering Center (SSEC) at the University of Wisconsin, and the Satellite Applications Branch (SAB) of the National Environmental Satellite, Data and Information Service. HRD meteorologists are working with the latter two groups to evaluate VAS [VISSR (Visible and Infrared Spin-Scan Radiometer) Atmospheric Sounder] temperature and humidity soundings and cloud-drift and water-vapor wind estimates. Cooperative studies with NMC are aimed at improved objective analyses of the ODW observations and tests of the usefulness of the data in hurricane-track numerical prediction models.

During Floyd, HRD continued its program of real-time objective analysis of ODW data. Preliminary wind analyses at 500 and 850 mb incorporating the ODW data, as well as satellite and rawindsonde winds from the standard network, were completed < 1 h after the end of the ODW flights. Final analyses at 200, 500, and 850 mb, which also incorporated gridded data from the NMC Regional Analysis and Forecast System analysis, were available 1 h later. These products confirmed the usefulness of the ODW data in describing winds over the normally data-void Gulf of Mexico.

Two P-3 flights were conducted to monitor Floyd's inner core as it moved from west of Key West to south of Miami. HRD scientists on site at NHC used a microcomputer[1] to prepare real-time objective analyses of flight-level data. The analyses tracked changes of tangential wind speed and pressure as a function of radial distance from the storm center. HRD also conducted operational tests of software that determines the track of the storm center based upon flight-level observations and estimates the motion and position of the storm at the time of the next official forecast.

On September 8, 1988, Tropical Storm Florence was the subject of a synoptic-flow experiment. At this time, Florence's maximum low-level winds were about 25 m s^{-1} and the system was nearly stationary in the Gulf of Mexico ~ 150 km north of the Yucatan Peninsula. Its future track was highly uncertain. ODW data and flight-level observations were transmitted to NHC where HRD researchers objectively analyzed the data and noted that the closed cyclonic circulation of the storm was clearly identified at 850 mb, but, at 500 mb, the wind field was dominated by south-southwesterly flow associated with a trough located 200 to 300 km west of Florence. The observations and the objective analyses clearly indicated that Florence would soon begin accelerating northward. About 5 1/2 h later, reconnaissance aircraft and the GOES (Geostationary Operational Environnmental Satellite) East satellite confirmed that Florence was beginning to move northward. In view of the subsequent change in direction and the intensification of Florence, these flights obtained a very interesting data set that was useful in real time for the hurricane forecasters and that will be used extensively in subsequent research.

Florence became a minimal hurricane and brought heavy rains, gusty winds, and high tides to southeastern Louisiana and southern Alabama and Mississippi before making landfall about 24 h after the end of HRD's synoptic-flow experiment. During the late afternoon and early evening of September 9, HRD staff on board a NOAA P-3 aircraft monitored changes in the structure of Florence as the center of the storm crossed the Louisiana Delta and moved toward the Louisiana-Mississippi border. During the first part of this flight, scientists obtained data that will serve as "ground truth" for rain rate and surface wind speed estimates made by the special sensor microwave imager (SSM/I) on the DMSP (Defense Meteorological Satellite Program) satellite. Duing the second part of the flight, they gathered observations that should provide insights on the weakening of the hurricane as it crossed the Louisiana Delta.

Hurricane Gilbert was the subject of several flights of the NOAA P-3 aircraft from September 11 to 19, 1988. Before landfall on the Yucatan Peninsula, Gilbert was the most intense hurricane that has ever been recorded in the Atlantic basin, with a minimum central surface pressure of about 885 mb. Maximum flight-level winds were ~ 80 m s^{-1} and were 10 to 15 km from the storm center. At larger radii, the flight-level winds decreased rapidly. When Gilbert emerged from Yucatan, the hurricane had a significantly different character. The minimum surface pressure was about 950 mb and the maximum flight-level winds were 40 to 55 m s^{-1}. The maximum winds were ~ 110 to 130 km from the center, and the winds decreased slowly outward from the radius of maximum winds. It was anticipated that Gilbert might regain its previous strength over the western Gulf of Mexico, but this did not prove to be the case. The data collected by the P-3's may allow researchers to determine why Gilbert failed to regain its previous intensity.

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[1]HRD permanently installed a relatively powerful microcomputer at NHC before the start of the 1987 hurricane season. This computer is dedicated to real-time analyses of P-3 aircraft data. The computer receives data from the aircraft through the Aircraft-Satellite Data Link and is connected to larger computers at AOML.

The response of the Gulf of Mexico to Gilbert's strong winds was the subject of five P-3 flights. This work was concentrated on the area between Yucatan and Texas. HRD deployed airborne expendable current profilers (AXCP's) and bathythermographs (AXBT's) along and behind Gilbert's track. AXCP's and AXBT's were dropped ahead of the storm to determine the prestorm thermal structure of the Gulf of Mexico. A second research flight dropped AXCP's in the wake region behind the storm. At nearly the same time, a NOAA P-3 flight dropped AXBT's in Gilbert's core. The remaining two flights occurred after Gilbert made its final landfall in Mexico. On these flights, AXCP's were dropped along the track that Gilbert had followed 1 to 3 days earlier. Based upon a comparison of observations from different missions, surface and mixed-layer temperature changes of 3° to 4°C were observed. The oceanic wake experiment is a cooperative effort with scientists at the U.S. Naval Postgraduate School.

On September 11, 1988, HRD conducted a hurricane energetics experiment with the two P-3 aircraft when Gilbert was in the Caribbean Sea about 250 km south of Santo Domingo and had a minimum surface pressure of 971 mb and maximum flight-level wind speeds of 35 to 40 m s^{-1}. The inner aircraft flew "L" patterns in the core of the storm and obtained an excellent set of observations with the new Doppler radar system. The outer aircraft dropped ODW's to observe Gilbert's thermodynamic structure 200 to 400 km from the center and attempted to determine the three-dimensional kinematic structure of the hurricane with the prototype Doppler radar.

A rainband experiment was flown on September 12, 1988, when Gilbert's eye was over the eastern tip of Jamaica and the storm had a minimum central pressure of 961 mb and maximum flight-level wind speeds of $\sim$ 45 m s^{-1}. Throughout the experiment, a convective rainband was approximately 130 km southeast of the center of the eye in an area with maximum low-level wind speeds of $\sim$ 35 m s^{-1}. The band was the most well-developed and long-lasting that HRD has monitored since it began conducting rainband experiments in 1981.

A cooperative program between NSSL and HRD seeks to obtain upper air soundings before, during and after hurricane landfall by use of a mobile CLASS (Cross-Chain Loran-C Atmospheric Sounding System) installed on an NSSL van. As Gilbert approached the west coast of the Gulf, NSSL personnel drove two vans from Norman, Oklahoma, to Kingsville, Texas, about 200 km north of Brownsville. An HRD scientist joined the NSSL group at Kingsville. Soundings were launched at 3-h intervals and significant observations were reported to NHC. Since Gilbert's center moved inland in Mexico about 400 km south of Kingsville, the soundings were not made in strong winds. Good data were obtained adjacent to the outer bands of the hurricane and the feasibility of using the NSSL vans was confirmed.

During the Gilbert event, HRD scientists again analyzed flight-level observations from the NOAA aircraft in real time at NHC. They estimated the location of the storm center as a function of time using aircraft and satellite center fixes and produced objective charts of the storm track. Plots of tangential wind speed and D-value were produced in storm-relative coordinates. These charts were made available to the hurricane forecasters within 1 to 2 min of being plotted.

On September 1, 1988, in cooperation with SSEC, SAB, NMC, and NHC, HRD conducted an experiment to compare ODW temperature and humidity observations with thermal retrievals from the VAS radiometers on GOES East. HRD used both NOAA P-3 aircraft to obtain uniform ODW coverage in the area bounded by 21°N, 66.5°W, 31.5°N, and 80°W. The ODW's were released at 165-km intervals.

A clear region was selected for the experiment so that the VAS retrievals would not be contaminated by clouds. The ODW's worked quite well, and SSEC staff indicated that an excellent set of VAS retrievals was obtained. HRD will postprocess the ODW data, obtain all relevant satellite, aircraft, and radiosonde observations, objectively analyze the observations, and compare analyses with and without satellite data.

PERSONNEL

Composition of Full-Time Staff - FY-88

Degree	HRD Personnel
Ph.D.	13
M.S.	9
B.S.	8
B.A.	1
Paraprofessional	6

Composition of All Staff (Full- and Part-Time) - FY-88

Degree	HRD Personnel
Ph.D.	13
M.S.	11
B.S.	8
B.A.	1
Paraprofessional	6

UNIVERSITY RELATIONS

Cooperative Research[2]

Organization	Research/Cooperative Investigator
Desert Research Institute, University of Nevada	The Ice Phase and Electrical Evolution in the Hurricane - Dr. John Hallett
National Center for Atmospheric Research	Hurricane Rainbands III: Mesoscale and Convective-Scale Structure - Drs. Margaret A. LeMone and Gary M. Barnes
State University of New York/Albany	Synoptic- and Subsynoptic-Scale Diagnostic Studies of Tropical Convective Systems in Weakly Baroclinic Environments - Dr. Lance F. Bosart
State University of New York/Albany	Synoptic-Scale Influences on Hurricane Intensity - Dr. John Molinari
University of Chicago	Aerial and Ground Survey of Hurricane Damage - Dr. T. Theodore Fujita
University of Massachusetts	Microwave Remote Sensing Measurements of Ocean Surface Winds in Hurricanes - Dr. Calvin T. Swift
University of Washington	Analysis of AOML/HRD P-3 Doppler Radar Data - Dr. Robert A. Houze, Jr.

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[2]Research summaries are in section entitled "Cooperative Research Projects."

University-Associated Speakers at HRD

1988

February 17	Nova University Dr. Julian McCreary: "The Ocean Response to Strong Offshore Forcing by Mountain-Pass Wind Jets: Model Results"
March 21	Oregon State University Professor Larry Mahrt: "Limit Cycle Mixing"
May 27	University of Oklahoma Mr. Eugene W. McCaul, Jr.: "Hurricane-Spawned Tornadoes"
June 7	University of Oklahoma Dr. Hartmut Kapitza: "A Conjugate Gradient Poisson Solver for a Nonhydrostatic Mesoscale Meteorological Model"
June 8	University of Maryland Dr. Chung-Hsiung Sui: "Westerly Wind Burst and Air-Sea Interaction Over the Equatorial Pacific Ocean"
July 27	Florida State University Dr. Noel Davidson: "Tropical Cylone Genesis During the Australian Monsoon Experiment"
August 24	State University of New York/Albany Dr. John Molinari: "Environmental Interactions and Tropical Cyclone Intensity"
August 30	University of California at Los Angeles Professor Roger Wakimoto: "Non-Supercell Tornadoes"

Adjunct Faculty Members (1988-1989)

HRD Scientist:	Dr. Lloyd J. Shapiro
Affiliation:	University of Miami
Discipline:	Atmospheric Science
HRD Scientist:	Mr. Howard A. Friedman
Affiliation:	Embry-Riddle Aeronautical University
Discipline:	Meteorology

FY-88 PROGRAMS - FY-89 PROJECTIONS

LABORATORY RESEARCH

1. Observational Hurricane Studies

1.1 The Synoptic-Scale Environmental Flow Around Mature Hurricanes

Goal

The synoptic-flow experiments are designed to investigate the steering currents on the periphery of mature hurricanes. ODW's are dropped from the NOAA P-3 aircraft to obtain the data required for these studies. The ODW's measure temperature, relative humidity, and pressure, and receive Omega navigational signals from eight transmitters. The navigational signals allow the winds to be computed. With these data, the synoptic-scale flow around a hurricane can be determined from the surface to 400 mb far more accurately than is possible with only the operational network.

Accomplishments (FY-88)

Postprocessing of ODW data was completed for Hurricanes Emily and Floyd of 1987, HRD's Ocean Cumulus Experiment, the Taiwan Mesoscale Experiment, the Pacific Marine Environmental Laboratory's Ocean Storms, and the NSSL's Gulf of Mexico Experiment. A total of 375 ODW's was processed. HRD base-lined (that is, carried out prelaunch performance checks for) all ODW's used by ERL.

Six ODW's were dropped in the eye of Hurricane Emily on September 22, 1987. At this time, Emily's eye diameter was 15 to 20 km, and the central pressure was $\sim$ 960 mb. The ODW, flight-level, and radar data are being used to determine the thermodynamic, kinematic, and precipitation structure of Emily's eye and eyewall. In Emily, the Office of Aircraft Operations (OAO) aircraft measured the highest values of 1-s updrafts and downdrafts that they have recorded in a hurricane. The ODW thermodynamic profiles show that Emily's eye was much drier than a sounding that was obtained in Gloria's (1985) eye at the time that its central pressure was 922 mb.

Plans (FY-89)

Cooperative studies with NHC and NMC that examine the impact of the ODW data on the operational analyses and hurricane track models will continue. Data collected during the 1988 hurricane field program will be used in diagnostic and prognostic studies of hurricanes. Additional ODW data will be obtained on one or two days during the 1989 hurricane season.

1.2 Mesoscale Precipitation Features in Mature Hurricanes

Goal

The purpose of this research is the identification of the mesoscale and convective-scale features in mature hurricanes and a description of the basic organization and structure.

Accomplishments (FY-88)

Analysis of data from Hurricane Norbert (1984) has continued. Airborne Doppler radar wind data show that the tangential wind maximum slopes upwind with increasing altitude. The radial wind at 1 km altitude shows inflow in the front of the storm and outflow at the back. By 3 km altitude, the radial flow switches to inflow in the rear of the storm and outflow in the front. The vertical velocity maximum is to the left of the storm track at all levels and slopes downwind with increasing altitude.

Norbert's horizontal wind components were partitioned into a horizontal mean wind (as a function of altitude) and a perturbation wind. The perturbation wind was then partitioned into the mean vortex (a function of radius and height, wavenumber 0), and a perturbation from the mean vortex (higher order wavenumbers). The wind partitioning showed that the mean vortex was characterized by a tangential wind maximum of 52 m s^{-1} at 26 km radius and 1.5 km altitude. This wind maximum sloped outward with increasing altitude. Two channels of upward vertical velocity ($\sim$ 1 m s^{-1}) were found. One channel was along the inside of the tangential wind maximum, sloping outward with height. The second vertical velocity maximum was nearly vertical and was centered at 16 km radius. This appears to have been the remains of an old inner eyewall. Downward motion dominated the area inward of 13 km radius.

An extensive analysis of microphysical observations surrounding Norbert was carried out. The microphysical data were mapped in a plan view to derive the spatial distribution of the particle types. The results at 6 km altitude showed the ice particle concentrations to be rather uniform in the azimuthal direction surrounding the storm, even though the radar reflectivity field was quite asymmetric. The highest ice particle concentrations were in the eyewall. The concentrations decreased with increasing radius. Good spatial correlation between the particle concentrations and the vertical velocity peaks was found.

A retrieval technique was used to obtain Norbert's thermodynamic variables from the Doppler wind analysis. The goal of this effort was to deduce the fractional amounts of water in the vapor, liquid (both cloud and rain), and solid (ice) states. Ice and rain water were determined from the radar reflectivity data. Cloud water and water vapor were deduced using the thermodynamic and microphysical retrievals.

Airborne Doppler wind data collected in Hurricane Gloria (1985) are being blended with the HRD objective analysis scheme (originally developed for ODW data; see project 6). The Doppler wind data set, and retrieved pressures, covering a 150 x 150 km area centered on the storm, are incorporated into a nested version of the objective analysis scheme. The resultant analysis shows the wind field on scales ranging from that of the eyewall to that of the subtropical ridge.

Plans (FY-89)

Reports describing the kinematic and microphysical structure of Hurricane Norbert's eyewall will be completed. Work will continue on the eyewall water budget analysis in Norbert.

Analysis of data from an eyewall water budget experiment flown in Hurricane Emily (1987) will be started. The Emily data were obtained as the storm was deepening at $\sim$ 2 mb h^{-1} in contrast to the Norbert data set, which was obtained when the storm was filling at $\sim$ 2 mb h^{-1}.

A climatology of vertical incidence reflectivity and vertical velocity data collected in mature hurricanes since 1983 will be started. HRD has $\sim$ 140 radial flight legs from six hurricanes with vertical incidence data.

We shall continue to incorporate airborne Doppler wind data into the HRD objective analysis scheme for the Hurricane Gloria synoptic-flow experiment. Preliminary results show that the airborne Doppler wind analyses can provide information on the structure of the vortex core that can be incorporated in the nested objective analysis scheme. Similar work with data from a synoptic-low experiment in Hurricane Emily will be started.

1.3 Convective Rainbands in Hurricanes

Goal

The goal of this research is an assessment of the role of hurricane rainbands in the modification of hurricane structure and intensity. Rainband downdrafts can modify the thermodynamic properties of boundary-layer air flowing toward the storm center. The impact of this effect on the eyewall convection will be studied. The rainband-hurricane interaction, as affected by the rainband location, structure, intensity, and propagation, will be documented.

Accomplishments (FY-88)

This research is being carried out in cooperation with scientists at NCAR. A study of Hurricane Raymond (1983) has continued. We examined, in detail, a Doppler wind field that was composited with respect to a radar echo of $\sim$ 10 km in scale. The echo was moving along the rainband which, in turn, was trailing the storm. A maximum of the tangential wind velocity was found in the moving cell. The momentum associated with the cell was found to be higher than that seen in the environment of the cell. The origin of this higher momentum air is unknown.

Lower fuselage radar composites for Hurricane Paine (1986) have been constructed. They show a storm with relatively low reflectivity and an eyewall that appeared to be forming at the time of the P-3 flight.

Analysis of flight-level data and radar reflectivity data from Tropical Storm Isabel (1985) has started.

Plans (FY-89)

HRD staff will construct radar reflectivity and Doppler composites for Isabel and Paine. The developing eyewall in Hurricane Paine will be studied. The studies of Hurricanes Raymond, Paine, and Tropical Storm Isabel will be completed.

1.4 Vortex Motion and Dynamics

Goal

This research is directed toward a better understanding of hurricanes through detailed analysis of observations from research aircraft and through formulation of relatively simple quasi-analytical models. The project also includes an effort to improve hurricane forecasting through real-time analysis and interpretation of aircraft data.

Accomplishments (FY-88)

Since 1977, HRD has collected more than 800 radial profiles of in-situ aircraft observations in 16 tropical cyclones. In FY-88, the analysis of a backlog of unprocessed flights from previous years was completed. New observations from 1987 Hurricanes Emily and Floyd were also analyzed. This data base verifies that the axisymmetric primary circulation is in gradient balance with the pressure field and that the development of the primary circulation in hurricanes follows the concentric convective-ring model that has been proposed.

Calculations with a quasi-analytical linear model of a moving hurricane-like barotropic vortex have shown that a vortex with cyclonic flow throughout, on a beta plane, exhibited unphysically fast poleward motion. Anticylonic flow introduced at the periphery of the vortex reduced the speed of the poleward motion because the net Coriolis force acting upon the air in the vortex was proportional to the relative angular momentum (RAM) of the axisymmetric flow. Calculations completed this year indicate that the wave flux of angular momentum due to an asymmetric perturbation acts to adjust the axisymmetric RAM toward zero. The excessive poleward motion arose because the perturbation forced by the beta effect at zero frequency is a normal mode of the vortex, as is the perturbation at the most anticyclonic orbital frequency of the mean flow in a vortex with an annulus of anticylonic flow far from the center. When the vortex is cyclonic throughout, the three normal modes have zero frequency: a stable mode and a conjugate pair of barotropically unstable modes with e-folding time of $\sim$ 75 days. When the mean vortex has zero RAM, only the stable normal mode remains at zero frequency, while the unstable modes move to the most anticyclonic orbital frequency and their growth rate increases by an order of magnitude. In both cases, the normal modes' importance lies in resonance at a particular frequency, rather than in their stability or instability, because the unstable modes grow so slowly.

In FY-88, a MicroVAX II computer, dedicated to real-time analysis of airborne hurricane data, was installed permanently at NHC on a protected power supply. This computer was provided with good communications to computers and terminals at HRD. Programs to determine track, structure, and intensity change, and to monitor the progress of the aircraft mission, were developed.

Plans (FY-89)

A study will be carried out to determine whether objectively determined hurricane tracks can compete with operational tracks and best tracks for the initialization of objective forecast aids.

Further study, with the linear theoretical model described above, will examine the normal modes' stability and wave transports. The diagnostic, semispectral, vortex motion model will be reformulated as a prognostic model that is Fourier-transformed in time, only, rather than in time and azimuth. The reformulated model should be simpler than the original model so that inclusion of nonlinear, baroclinic, or frictional effects should require less labor.

The real-time data analysis system is largely complete. During FY-89, the user interface will be improved and the system will be integrated into NHC's operations and communications. Development of new products in response to experience and expressed needs of the users will be a continuing effort, as will adaptation of the system to the VAS Data Utilization Center (VDUC) as the VDUC becomes operational.

1.5 Microphysical Studies in Hurricanes

Goal

The goal of this research is a description of the water contents, liquid and ice particle size distributions, particle number concentrations, and the particle phase partitioning within the dynamic framework of hurricanes. The microphysical characteristics of convectively active regions will be compared with the characteristics of more stratiform regions of hurricanes.

Accomplishments (FY-88)

The microphysical data from Hurricane Norbert (1984) on September 22, 1984, were processed. Particle number concentrations, size distributions, water contents, and other characteristics were computed as 5-s averages for the entire storm. A list of major particle types as a function of time during an aircraft penetration of the strongest reflectivity area in the eyewall was also completed.

A radar reflectivity/ice water content (Z-M) relationship was derived for the stratiform area of Hurricane Norbert. The relationship was obtained by calculating the average measured flight-level reflectivity from vertical radar cross sections at selected times and then by calculating the reflectivity from the ice particle size spectra using a fixed density. The density that produced the same average measured radar reflectivity was then calculated. New ice water contents and radar reflectivities for the selected areas were computed using the proper density. The Z-M relationship was derived by means of a linear least-squares fit to the calculated reflectivity and ice water content data. The Z-M relationship is useful for computing the ice water content in areas without direct microphysical observations. No other Z-M relationships in the ice regions of hurricanes are available.

Plans (FY-89)

The microphysical data from Hurricane Emily (1987) will be analyzed. Most of these data were obtained at temperatures below freezing. Substantial amounts of data were obtained in stratiform precipitation and a stratiform spiral was flown.

Work will continue on a comprehensive study of the shapes of ice particle distributions in hurricane clouds and in nonhurricane tropical convection. This work will include the application of diagnostic microphysical models to help define the relative importance of the processes shaping the observed ice distributions.

A study is in progress that attempts to relate eyewall development and hurricane intensity changes to the locations, patterns, and stage of development of stratiform precipitation areas. HRD will attempt to determine whether stratiform precipitation areas influence the development and evolution of major convective features of storms.

Studies of the trajectories of ice particles from the eyewall and convective features of the rainbands will be continued. This work will be carried out in cooperation with scientists from NCAR. Numerical models of hydrometeor growth will be used in an attempt to assess how much of the ice mass in hurricane stratiform precipitation areas is added in-situ by particle growth due to mesoscale ascent and how much is due to transport into these regions from more convective features.

1.6 Convective and Mesoscale Structure of Landfalling Hurricanes

Goal

The purpose of this research is the analysis and interpretation of digital radar data that are recorded at National Weather Service (NWS) offices during the landfall of hurricanes. The emphasis of the analyses is on the description of important changes in the magnitude and the patterns of rainfall that occur as hurricanes approach coastal areas and make landfall.

Accomplishments (FY-88)

A study of the temporal and spatial variations of rainfall in the inner core regions of Hurricanes Alicia (1983) and Elena (1985) was completed. The observations were made before landfall when the inner core regions of these storms were over the ocean. Rainfall was calculated for the area within 75 km of the storm centers. Area-averaged rain rates were computed for the eyewall and inner rainband areas. There was considerable variability in the eyewall rain rate over periods of 1 to 3 h. Most of the variability was accounted for by convective areas having rain rates > 10 mm h^{-1}. The percentage of the eyewall region covered by rain rates > 10 mm h^{-1} varied from 4% to 20%.

The contribution of rain rates > 10 mm h^{-1} to the total eyewall rain rate averaged about 50%, but ranged from < 20% to > 75%. The area-averaged rainfall variations in the eyewall were caused by small mesoscale areas of convection that formed ahead of the storm track, increased in size as they moved downwind, and dissipated on the left side of the storm. Rain rates > 10 mm h^{-1} in the inner rainbands accounted for an average of ~ 15% of the area-averaged total.

On the average, the maxima of the eyewall and inner rainband rain rates were in the left-front quadrant for Alicia and the right-front quadrant for Elena. At the time of the calculations, Alicia was moving toward the northwest at ~ 1.5 m s^{-1} and Elena was moving toward the west-northwest at ~ 4.5 m s^{-1}. The difference in the spatial orientation of the rain maxima relative to the forward motion of the hurricanes is consistent with theoretical calculations of the distribution of boundary-layer convergence. The spatial orientation of the rain-rate maxima in Alicia changed abruptly about two-thirds of the way through the calculations. Initially, the rain-rate maxima in the eyewall and inner rainbands were in the left-front quadrants. The maxima shifted to the right-front quadrant without any corresponding change in the storm motion. The change in the orientation of the maximum rain rate occurred at about the same time that Alicia developed a double eyewall structure.

Radar reflectivity data were recorded at NWS offices in Key West and Miami as Hurricane Floyd (1987) passed south of Florida. At that time, Floyd was a minimal hurricane and the precipitation structure was largely stratiform.

Plans (FY-89)

Airborne and land-based radar reflectivity data are available almost continuously for Hurricane Elena for 5 days. During this time, Elena evolved from a tropical storm to a major hurricane with a minimum central pressure of 951 mb. The evolution of Elena's precipitation structure will be described and the results will be compared with previous studies of Hurricanes Allen (1980) and Alicia.

HRD recorded airborne Doppler radar data on six of the flights in Elena. Three-dimensional wind fields will be constructed from the Doppler data within ~ 50 km of the storm center to determine the changes in the radial and tangential wind fields that occurred as Elena intensified from a tropical storm to a major hurricane.

1.7 Hurricane Boundary-Layer and Air-Sea Interaction Studies

1.7a Boundary-Layer Studies

Goals

Several hurricanes are being investigated to determine the influences of rainbands on the hurricane boundary-layer (HBL) structure and the extent to which these influences may affect the dynamics of the vortex. Oceanic surface wind observations, made by NOAA platforms, are being compared with NOAA aircraft measurements to develop relationships between flight-level winds measured by reconnaissance aircraft and the winds at the underlying surface.

Accomplishments (FY-88)

Analyses of the kinematic and thermodynamic structure of the HBL near an outer rainband in Hurricane Earl (1986) continued. Results indicate that outer rainbands can exert a strong influence on HBL structure. The observations show that surface equivalent potential temperature (θ_E) on the inner side of the rainband is several degrees lower than that found on the outer side. One particularly extreme case of gust front modification produced an 18 K decrease of surface θ_E. Such extreme HBL modification acts to destroy the mixed layer. Aircraft and ODW soundings adjacent to the Earl rainband indicated the presence of disturbed mixed layers in various stages of recovery on the inner side of the band. Such disturbances might have consequences for eyewall convection and storm intensity if the disturbed surface air were to reach the eyewall before recovering to previous undisturbed θ_E values.

Simple mixed-layer model calculations were made for trajectories of air flowing from downdraft modified regions toward the eyewall for Hurricanes Floyd (1987) and Earl. These calculations indicate surface θ_E increases of only 20% to 50% of the requirement to reach "undisturbed" conditions. HBL modification may, therefore, prove to be an important mechanism governing transitional intensity changes of hurricanes.

Study of a data base of aircraft-buoy comparisons shows that relationships between aircraft and buoy-measured winds are strongly dependent upon stability and less clearly dependent upon altitude. With unstable conditions (sea-air temperature differences of $> 1\,°C$), surface winds are 76% (range 62% to 90%) of flight-level winds. With stable conditions (sea-air temperature differences of $< -1\,°C$), surface winds are 54% (range 44% to 64%) of flight-level winds.

Plans (FY-89)

A paper, entitled "Boundary-Layer Structure and Dynamics in Outer Hurricane Rainbands, Part I: Mesoscale Rainfall and Kinematic Structure; and Part II: Thermodynamic Structure, Downdraft Modification, and Mixed-Layer Recovery," will be completed.

A manuscript, entitled "Estimating Oceanic Surface Winds in Hurricanes: Relationships Between NOAA Aircraft Reconnaissance and Buoy Platforms," will be completed. This paper will contain results of comparisons between NOAA aircraft and buoy wind observations that were gathered over the past 10 years.

Analysis of airborne Doppler data from a Genesis of Atlantic Lows Experiment (GALE) rainband study that was conducted in March 1986 will be completed. Airborne Doppler radar data from the Hurricane Earl rainband experiment will be reanalyzed to extend the work to the convective scale.

1.7b Air-Sea Interaction Studies

Goals

The goals of this project are the development of a surface wind analysis scheme for tropical cyclones and a study of the structure and dynamics of the atmospheric and oceanic boundary layers in tropical cyclones.

Accomplishments (FY-88)

A total of 30 usable AXCP's was deployed from a NOAA P-3 aircraft in eastern Pacific Hurricane Norbert (1984) and Atlantic Hurricane Josephine (1984). In addition, three drifting buoys were deployed ahead of Josephine and four were deployed within Atlantic Hurricane Gloria (1985).

The Norbert observations revealed a divergent cyclonic circulation within the oceanic mixed layer that was similar to that predicted by recent numerical model simulations. Maximum mean mixed-layer currents of 1.2 m s^{-1} were observed. Below the thermocline, a weaker anticyclonic circulation was observed. The Josephine observations revealed a complex eddy pattern induced by the interaction of the storm with the ocean subtropical front. The Gloria buoy observations revealed strong, divergent surface currents in the right-rear quadrant, similar to the Norbert observations.

Surface wind, pressure, and temperature observations from land stations, ships, coastal marine stations, and offshore rigs were analyzed in a composited, storm-relative coordinate system for Tropical Depression (TD) #2 (August 9-10, 1987) and Hurricane Floyd (October 12-13, 1987).

The analyses for TD #2 revealed a surface trough oriented north-south beneath an upper level divergent asymptote. A broad circulation center embedded in the south end of the trough dissipated, while a new center formed at the north end of the trough, just before landfall. The new center formed adjacent to intense convection that developed beneath the strongest upper divergence. Observations from automatic weather stations on rigs in the Gulf of Mexico showed that a large area of gale-force winds developed upstream from the convection. At some locations, sustained winds, stronger than gale force, blew for > 12 h. A maximum sustained wind of 51 kt was observed, as was a maximum wave height of 14.7 ft. Only a few of these rig observations were received in real time at the NHC and no reports were received from the reconnaissance flight in the high-wind quadrant of the system. As the center made landfall, several comparisons between 5,000 ft flight-level winds and the rig-reported winds were made. These observations showed rig winds equal to, or slightly greater than, the flight-level winds.

Warm advection ahead of Hurricane Floyd helped to strengthen a frontal zone across south Florida. This zone moved northward as a warm front early in the day on October 12, 1987. A pressure perturbation that was observed to move through central Florida during the day was associated with strong convection. A secondary circulation center formed south of the perturbation along the frontal zone northeast of Floyd. Analysis of data from a morning flight showed that the cold air north of the front had been entrained into Floyd's circulation and formed a cold front extending south-southeast from the center. As the pressure perturbation moved off the Florida east coast, the front moved southward again.

This sequence of events appeared to push the cold air southward over the Florida peninsula. By the time Floyd passed offshore from Miami in the early evening of October 12, the colder air had passed offshore. This created a stable boundary-layer situation over the south Florida peninsula that prevented near hurricane-force winds, measured at flight level, from penetrating to the surface. In some locations, surface winds were > 50% of flight-level winds at 1,500 ft.

In summary, two tropical systems were studied that occurred during the 1987 hurricane season: one a depression that produced surface gale-force winds for > 12 h, with a maximum value near 50 kt, and the second a hurricane that produced scattered surface sustained wind measurements greater than gale force for 2 to 3 h, with maximum sustained measured surface winds of 47 kt. In the former, minimum surface pressure was 1008 mb, while in the latter, minimum surface pressure was 994 mb. In the former, maximum flight-level wind was 35 to 40 kt, while in the latter, it was 70 to 75 kt.

Work on the determination of surface winds using the stepped-frequency microwave radiometer (SFMR) from the P-3 aircraft has continued. A new on-board algorithm for real-time wind determination was tested during the 1988 hurricane season.

Plans (FY-89)

In collaboration with NHC, a detailed evaluation of the SSM/I instrument on a DMSP satellite will be carried out to determine its usefulness in measuring surface winds in and around hurricanes. Special flight patterns will be flown with the two P-3 aircraft, one of which will be equipped with the SFMR for remote sensing of the surface winds and which will be coincident with SSM/I overflights.

Work will begin on an effort to synthesize various types of surface data into an overall surface analysis for tropical cyclones. This effort will be built around the inputs available from the NOAA aircraft and will include the SFMR wind estimates as well as planetary boundary-layer model estimates based upon flight-level measurements. Other data sources will also be incorporated where available. These sources include fixed buoys, drifting buoys, satellite microwave and low-cloud motions, ship and automated weather observations from rigs, and exposed coastal locations. The long-term goal is to provide a surface analysis in real time for forecast and warning purposes.

We will continue to use the improved version of the SFMR algorithm on the aircraft during the 1989 season and begin real-time transmission of surface winds to NHC via the new aircraft satellite data link format.

Analyses of the 1984-85 ocean response and AXCP data will also continue. Analysis of airborne-Doppler-derived near-surface winds will be incorporated into low-level aircraft in-situ measured winds and SFMR-derived surface winds to produce a surface wind field for incorporation into an ocean response model.

1.8 Tropical Cyclone Supercell Structure

Goal

The goal of this project is an understanding of the formation and evolution of large supercells within tropical cyclone circulations.

Accomplishments (FY-88)

Large convective bursts that last from 12 to 24 h and consist of several shorter period convective pulses sometimes occur near tropical cyclone maximum wind (eyewall) regions. These events disrupt trends in storm deepening for a day or two. Following this disruption, rapid deepening sometimes occurs.

Analysis has continued on the Hurricane Norbert (1984) supercell data of September 22, 1984. Preliminary results reveal that there was a west-northwest tilt to the core of the cell as well as a west-northwest tilt to the circulation center. The center at 9 km altitude was displaced 15 km west-northwest of the center at 3 km altitude. This characteristic suggests a strong easterly environmental shear. An analysis of satellite high-cloud motions confirmed that an upper level jet was impinging on the storm from the southeast. The Norbert synoptic analysis was compared with the analysis for another supercell storm, Hurricane Gladys (1975). High-cloud motions for this case revealed that a similar easterly jet was impinging on the storm at the time of supercell occurrence. Intense supercell convection was the consequence.

A large supercell was observed in Hurricane Diana (1984) just before rapid intensification. Frequent lightning discharges were observed by the Lightning Position and Tracking System (LPATS) Florida network and from aircraft. The radar reflectivity structure and the location on the south side of the circulation center was similar to both the Norbert and Gladys supercells. Preliminary analysis of the LPATS data indicates that the majority of lightning strokes from Diana during the daytime came from three 20-min convective bursts at roughly 90-min intervals. These bursts originated from the supercell region.

Plans (FY-89)

Analysis of aircraft data for the Norbert, Diana, and Gladys supercells will be continued. An effort will be made to construct a qualitative model of the thermodynamic, kinematic, and microphysical structure of a supercell. A climatology of tropical cyclone supercell events in the Pacific and Atlantic over the past 10 years will be started.

2. Quasi-Spectral Hurricane Model

Goal

The long-term goal is to predict the motion, intensity, and structure of hurricanes. To attain this goal, we must address the complex problem of interactions between different dynamic regimes and different physical processes in the three-dimensional moist atmosphere. To facilitate the division and synthesis of individual phases of the research, a general-purpose base model (code name, QVADIS) is under development. This model uses an accurate and flexible numerical method called the SAFER[3] method. A two-dimensional version of the QVADIS model, on nested multiple domains, has been completed. The focus of this project is now on the vertical interaction *in* the moist atmosphere.

Accomplishments (FY-88)

The two-dimensional QVADIS model, on movable, multinested horizontal domains, was completed and is being used in HRD projects 3, 5, and 6. The use of the model was straightforward in its application to vortex dynamics in project 5. In the application to the balanced vorticity equation for barotropic prediction (project 3), the model had to be extended to solve elliptic Poisson equations on the nested geometry. The application of the basic logic of QVADIS to data analysis (project 6), was more complicated than we anticipated because of irregular distributions of real observational data. However, the stubborn computational problems have now been resolved.

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[3]SAFER is the acronym for "Spectral Application of Finite Element Representation" and replaces the earlier name, QSTING.

In the history of numerical weather prediction, moisture and moist thermodynamical processes have been treated as additions to the dry case and subjected to various simplifications and parameterizations. Evidence is accumulating, however, that the gross parameterization of moist convection has reached the limit of usefulness for the hurricane models of the future. To fully understand the effects of vertical shears and horizontal asymmetry on hurricane motion, for example, a better formulation of mesoscale dynamics and convection is essential. The nested-resolution model takes care of the geometrical aspects of multiscale problems. Moist physics in multiscale interaction must be improved next.

Within the realm of reversible thermodynamics (which currently excludes microphysics of hydrometeors), it has been found that a great degree of simplicity is achieved by formulating all the prognostic equations strictly in terms of the conservation laws of mass, entropy, and momentum of the moist air. The use of pressure as a prognostic variable, or as the independent vertical coordinate, violates this principle, since there is no conservation law of pressure. In the theory developed here, pressure is a *diagnostic* variable of the thermodynamics.

The diagnostic determination of pressure is the most novel feature of this theory and requires a unified definition of moist entropy for saturated and unsaturated states. Although L. F. Richardson[4] lamented in his book that he was misled by Hertz's two separate formulas for entropy, nothing has been done until now. The same disjointed formulas are still listed in the current text books. This research has successfully derived the unified formula and has developed an efficient algorithm to solve it for pressure.

In this approach, there is no need to build two models, with and without the hydrostatic approximation, to test the difference. One model can do both by switching only the equation of vertical motion between the prognostic and the diagnostic forms. If hydrostatic balance is assumed, this model resembles the historical model developed by Richardson, with a few important differences. In Richardson's model, the diagnostic equation for the vertical motion is a first-order differential-integral equation. In this theory, it is a simple second-order elliptic equation that allows clean and consistent numerical solutions.

Plans (FY-89)

As the next step towards a three-dimensional moist model, a vertical two-dimensional model will be developed to investigate computational problems associated with vertical discretization of the stratified atmosphere. In view of the proposed new formulation of moist thermodynamics, this step appears necessary. The decision between finite-difference schemes and spectral representation in the vertical, the number of layers required for adequate modeling of moist physics, and preliminary tests of microphysical approximations are among the problems that require examination before we go to a fully three-dimensional model.

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[4]L.F. Richardson, Weather Prediction by Numerical Process, New York: Dover Publications, 1965. (First published in 1922.)

3. Development of a Nested Spectral Barotropic Hurricane Track Prediction Model

Goal

The objective of this study is the testing of the spectral nesting technique developed by HRD (project 2) in the context of the simplest system of equations that can be used for hurricane track prediction. This study will test the technique for the case where the model is initialized with real data and will determine its applicability to operational forecasting of hurricane tracks. This study will provide insight which will be needed for application of the method to fully three-dimensional simulations.

Accomplishments (FY-88)

The spectral nesting technique was adapted to the solution of the barotropic vorticity equation and the shallow-water equations on a Mercator map projection. The code was modified to allow for the solution of elliptic equations that are required in the vorticity equation model and in the initialization of the shallow-water equations. These models were tested using idealized simulations of an isolated vortex. Insight was gained into the grid systems and outer boundary conditions that will be required in real data simulations.

The deep-layer mean winds needed to initialize this model were obtained from data archives at NHC. To obtain these winds, data sets were transferred from the NAS 9000 computer in Maryland to NHC, from NHC to the AOML VAX computer, and from the VAX to the CYBER 855/205 system at Gaithersburg. A MicroVAX II computer was purchased to assist in data transfer from the Gaithersburg Cyber 855/205.

A nested-grid analysis algorithm, which is an integral part of the prognostic model (project 2), has been completed. Data selection is done on the AOML VAX; an input control deck to perform the analysis is constructed simultaneously. Data are sent to the CYBER 205 and analyzed results are transferred to AOML via the MicroVAX.

Plans (FY-89)

The analysis and prediction codes, which have been developed separately, will be combined. Since analysis and prediction may not necessarily be performed with the same geometrical arrangement of nested grids, some transformation of analyzed wind fields to the prediction model domain may be necessary.

The prediction model will be initialized with deep-layer mean winds and will be used to produce track forecasts. Tests will be made with data from Hurricanes Josephine (1984), Debby (1982), Gloria (1985) and Emily (1987). These storms are chosen because some ODW data are available for each case.

The hierarchy of cases for each storm will be: (1) NMC analyses without ODW's, (2) layer-mean ODW observations with NMC analyses as a background, and (3) layer-mean ODW analyses produced by the HRD cross-section technique with NMC analyses added in areas outside ODW coverage.

Since the NMC analyses do not contain an adequate representation of the storm circulation, model initialization in the first case will require filtering of the NMC analyses in the storm region and addition of a specified symmetric vortex. This procedure can be applied to any storm for which NMC analyses are available. Cases in which ODW data are included may require a vortex initialization.

Gloria and Emily, which have airborne Doppler data, will probably not need it, but Debby and Josephine may. The impact of vortex initialization in those cases without Doppler will be assessed.

4. Initialization of Tropical Cyclone Models

Goal

The objective of this study is the investigation of methods for initializing primitive-equation tropical cyclone models. Normal-mode initialization techniques have shown great promise for global models and some success in mesoscale models. This study will determine the applicability of normal-mode techniques to initialization of tropical cyclone models where surface friction, latent heat release, and nonlinear advection are important.

Accomplishments (FY-88)

The strategy of this study is to study initialization in the context of a highly truncated spectral axisymmetric tropical cyclone model. The code for a three-layer spectral tropical cyclone model in isentropic coordinates was adapted to the VAX computer. A highly truncated version of the model was developed and the initialization was studied analytically in a linearized version of the model. These results showed that normal-mode initialization is valid in the hurricane model, but the iterative technique used to solve the initialization equations converges too slowly to be practical. The results were generalized to the case where some nonlinearity was included. In this case, the iterative scheme diverges when the vortex amplitude becomes large. An alternative initialization scheme that allows the gravity mode amplitudes to come to a quasi-steady-state was found to produce much better results than the usual iterative techniques.

Plans (FY-89)

The results will be generalized to the fully nonlinear case. The question of uniqueness of the initialization equations will also be addressed in this part of the study.

5. Asymmetric Evolution of the Hurricane

Goal

The objective of this research project is a study of the asymmetric structure and evolution of the hurricane vortex, including its interaction with the large-scale environment. The asymmetries are central to the track prediction problem, as well as to the distribution of winds and convection in a moving vortex.

Accomplishments (FY-88)

A set of idealized experiments has been designed to investigate the influence of divergence and advective nonlinearities on hurricane motion and to study asymmetries caused by the beta effect. A multinested numerical model (project 2) was used in a one-layer, shallow-water (barotropic, primitive equation) form on a beta plane. In the first set of experiments, the environment was taken to be at rest. Comparisons were made with solutions from a nondivergent form of the model (project 3). The effect of divergence and total RAM on vortex motion and evolution were evaluated.

Scale analysis of the vorticity equation indicates that divergence should have a very small effect on hurricane motion. Numerical experiments with initial symmetric vorticities confirm that the vortex track is essentially unaffected by divergence, with only a 4% difference in total displacement after 72 h between the nondivergent simulation and those with shallow-water depths of 1 or 4 km. This result contradicts previous published studies of the effect of divergence.

The symmetric vortex develops asymmetries that have an influence far from the initial circulation. The asymmetries extend in all directions, but the strongest are associated with a series of alternating anticyclonic and cyclonic gyres that extend behind the vortex to the southeast. When the initial symmetric vortex is modified so as to have zero net RAM, the developing asymmetries are substantially reduced in strength.

Plans (FY-89)

Preliminary analyses indicate that the development of the alternating gyres behind the vortex with non-zero initial net RAM cause the total RAM to oscillate about zero. It appears that the adjustment process tends to move the RAM, unsuccessfully, toward zero. These ideas will be confirmed and extended with further experiments and analyses. Environments with nonuniform mean flow will be included and the model will probably be generalized to a two-layer version to investigate baroclinic interactions. The nature of the adjustment process will be investigated, as will the implications of the results for the initialization of operational hurricane track forecast models.

6. Objective Analysis of the Tropical Atmosphere

Goal

The goal of this research is the development of an objective analysis scheme that can be used for the large-scale tropics as well as for the environments of hurricanes. With the analysis scheme, we will evaluate tropical data and develop strategies for measuring wind and thermodynamic fields in the hurricane environment. The analysis scheme will incorporate ODW and other available data, such as rawinsondes, NOAA P-3, USAF reconnaissance data and satellite-derived products. Particular applications of the scheme are to examine ODW data from the HRD synoptic-flow experiment and daily large-scale analysis over the tropics.

Accomplishments (FY-88)

Three-dimensional wind analyses for the Hurricane Debby (1982) synoptic-flow experiment were published. Work on the temperature, surface pressure, and relative humidity analyses for Debby is also complete. Several diagnostics from the thermodynamic fields, including estimated precipitation rates from the Arakawa-Schubert parameterization scheme, have been calculated with reasonable results.

All airborne Doppler wind data from Hurricane Gloria (1985) have been analyzed, with quality control provided by this analysis package. Deviations from the analysis were sorted by wind speed; subjective quality control of the winds with largest deviations was carried out. An edited set of Doppler radar winds is now in final form. Further wind analyses for Hurricane Gloria, which are in progress, are based upon a nested-grid analysis algorithm, which is an integral part of Ooyama's prognostic model (project 2). Preliminary results at 500 mb are very encouraging.

Analysis of the Hurricane Josephine (1984) synoptic-flow experiment cases is well under way. Thermodynamic comparisons between VAS and ODW data in the wake of Hurricane Emily (1987) have been performed and verify many of the results obtained from an earlier study of Hurricane Debby.

The analysis code has been sent to several interested organizations, including the Naval Environmental Prediction Research Facility and Colorado State University. Complete documentation accompanied the code in each case. NMC has expressed some interest in using the code and the documentation has been sent to the Development Division, NMC. A cooperative project with NHC resulted in the analysis code being installed on the NMC NAS 9000 computer. It may be used daily to analyze height fields over the ATOLL (analysis of the tropical and oceanic lower layer) area from rawinsonde and TIROS (Television and Infrared Observation Satellite) data.

HRD and NMC analysis products were compared, by HRD, through a real-time analysis package during the 1988 hurricane season. This package will also be employed whenever ODW's are used in HRD field experiments.

Substantial time has been devoted to improving the reliability of communications between the NOAA P-3 aircraft and HRD's ground station at NHC. A new interactive program was written to edit the ODW data and is scheduled for real-time checkout during the 1988 hurricane season. Data that are at NMC and that consist of rawinsondes, commercial aircraft reports, TIROS geopotential heights, and NMC and NHC cloud-drift winds at 200 and 850 mb are being transferred through the NHC Data General computer, gathered by the HRD MicroVAX at NHC, and archived for future study. During the 1987 hurricane season these data were transmitted over phone lines, a process that proved to be unreliable and time-consuming.

Plans (FY-89)

A study of the thermodynamic data analyses for Debby will be completed. Analysis of the Josephine and Gloria data will continue, as will real-time analysis of the tropical atmosphere at the 850- and 200-mb levels. These analyses will be compared and evaluated with respect to current NMC and NHC products. The analysis package will be incorporated into airborne Doppler radar analysis software (project 1.2).

7. Studies of Tropical Climate

Goal

The goal of this research is the establishment of a climatology and time history of quasi-steady and propagating atmospheric disturbances over the tropical Atlantic. The relationship of the long-term variability of the winds to climatic fluctuations and hurricane cycles is under study.

Accomplishments (FY-88)

A study of the relationship of the quasi-biennial oscillation (QBO) to Atlantic tropical storm activity was completed. Monthly averaged 30- to 50-mb-layer zonal winds at Balboa, Canal Zone (9°N), were used to objectively determine the relationship of the QBO to Atlantic tropical storm activity during 1952-1986. The largest correlation was found between storm activity and the QBO in June, which is ~ 3 months before the central part of the hurricane season. Correlations with storm incidence for individual calendar months confirmed an approximate 2- to 3-month lead of the QBO relative to tropical storm formation.

The well-known downward phase propagation of the QBO implies an in-phase relationship between storm formation and the winds at about 50 mb near the equator. Although weak, winds at these levels may have a direct influence on developing tropical systems. Zonal winds filtered to remove periods of < 15 months were used to establish correlations between the QBO and tropical storm activity that are essentially independent of lag. For 1955–1986, it is estimated that the correlations have true skill explaining $\sim$ 30% of the variance in storm activity, with $\sim$ 25% of the variance explained on an independent forecast.

Recent results published by Labitzke and van Loon indicate that the phase of the QBO may be an indicator of the degree and nature of association between the 11-year solar cycle (as indicated by sunspot numbers or solar flux) and stratospheric and tropospheric parameters. In the present study, the relationship between sunspot numbers and tropical storm activity was investigated for 1952–1986. For all years taken together, or for only years during the west phase of the QBO, as classified by the 30- to 50-mb Balboa zonal wind during August–October, the correlation between storm activity south of 30°N and the August–October sunspot number was very small. For years during the *east* phase of the QBO, however, the correlation was large and positive, significant at about the 90% level. The estimated true skill is $\sim$ 10% of the variance.

This result implies that the QBO may be an indicator of the degree of association between an 11-year cycle and tropical storm activity in the Atlantic. Lag correlations indicate that the association is strongest for in-phase relationships. Consistent with these results, the in-phase association between sunspot numbers and 700-mb heights for August–October of 1952–1981 indicates a large area of significant correlations over western Africa, the genesis region for Atlantic tropical systems, only during the east phase of the QBO. The data themselves cannot, however, be used to determine whether the relationships are causal, or due to a near 11-year periodicity that is not caused by solar influences.

Plans (FY-89)

A paper describing the results of the research on the relationship between the QBO and Atlantic tropical storm activity will be prepared and submitted for publication. An investigation will be started to establish the Atlantic hurricane cycles and tropical wind variability associated with the 30- to 60-day oscillation, as well as the predictability of the cycles. The investigation will establish the hurricane cycles associated with the oscillation based upon records since 1900. The cycles will be related to objective indices of the oscillation, as well as Atlantic tropical wind variability.

8. Tropical Cyclone Awareness Research

Goal

The goal of this work is the development and testing of educational strategies that are designed to enhance awareness of tropical cyclones and to promote preparedness in tropical cyclone-prone areas.

Accomplishments (FY-88)

Work continued on a hurricane instructional program known as CALM (cognitive and affective learning model). The computer-assisted instructional component (cognitive module) of the CALM model was converted to the Apple II computer because of this computer's availability in the Dade and Broward school systems. A simple proof-of-concept test of the cognitive module was used to examine the hypothesis that "tropical cyclone awareness was created and/or enhanced by the educational treatment." Fifteen students from a Dade County junior high school took a pretest. On the following day, students completed the instructional units and a post-test was administered. The mean pretest score was 58.2%; the mean post-test score was 71.9%. Exposing students to the cognitive module of CALM appears to have increased their level of tropical cyclone awareness. However, further testing with a larger number of students is needed.

Plans (FY-89)

Proof-of-concept testing will be conducted in selected south Florida schools. The goal is to test about 150 junior and senior high school students during FY-89.

9. Storm Surge

Goal

The goal of the research is adaptation of the SLOSH (sea, lake, and overland surge from hurricanes) storm surge model to specific bays and estuaries for operational hurricane prediction.

Accomplishments (FY-88)

Two studies that evaluate the SLOSH storm-surge model for the Long Island Sound and the Pamlico Sound basins were completed.

Hypothetical storm-surge simulations were completed for the Florida Keys, Narragansett Bay, Buzzards Bay, and southeastern Louisiana. Preliminary storm-surge atlases were also completed for these basins.

Plans (FY-89)

Hypothetical hurricane storm-surge simulations will be made for Cape Canaveral and Biscayne Bay. Preliminary storm-surge atlases for these basins will be completed.

10. GALE

Goals

The goals of this research are a description of the rainbands observed during GALE and an understanding of the influence of the Gulf Stream on their formation and evolution.

Accomplishments (FY-88)

Analysis of microfilm images from the NWS radars at Wilmington and Cape Hatteras, North Carolina, yielded 149 rainbands from the Hatteras data and 109 from the Wilmington data for January 18 to March 16, 1986. The bands were classified by their location when first detected. Oceanic bands accounted for $\sim$ 60% of the total and 75% of the oceanic rainbands were first detected at or east of the Gulf Stream. Only $\sim$ 20% of the bands that formed over land, and survived to reach the Gulf Stream, intensified there. The Gulf Stream seems to have a greater influence on the formation of bands than on the modification of already mature rainbands.

The synoptic environments in which the rainbands formed were also classified according to the proximity of various types of frontal systems at the time of band formation. While rainbands were found in all of these synoptic classifications, rainband formation in cyclone warm sectors was most frequent. The formation of rainbands near the Gulf Stream was about equally frequent for all synoptic categories.

Plans (FY-89)

The study of GALE rainbands will be completed and results will be summarized for publication.

11. EMEX

Goals

The primary scientific objective of the Equatorial Mesoscale Experiment (EMEX) is a definition of the vertical profile of atmospheric heating produced by cloud clusters in the oceanic area around northern Australia. The accurate determination of this profile is of critical importance for both numerical weather prediction and climate studies. A second scientific objective is the documentation of details of the mesoscale circulation within the stratiform region of the tropical cloud clusters.

Accomplishments (FY-88)

This research was done in cooperation with scientists at the University of Washington (UW). UW converted a version of the NCAR Doppler analysis software for use in the pseudo-dual airborne Doppler analysis of EMEX data. UW has also adapted HRD software to process the vertical incidence data.

During a visit of UW scientists at HRD, two pseudo-Doppler analyses for an EMEX case were processed. These two analyses were used as a means to test the new software developed at UW, as well as to evaluate how well the pseudo-dual Doppler analyses describe the three-dimensional kinematic structure of the EMEX cloud clusters.

The results of the three-dimensional analyses of the cloud cluster wind field were very encouraging. The pseudo-dual Doppler analyses were able to describe the kinematic structure of a convective and a stratiform portion of an EMEX cloud cluster. The convective region was characterized by strong west-southwest winds (15 m s^{-1}) at 2.5 km, decreasing to southwest (11 m s^{-1}) at > 4.5 km (the altitude of the 0°C isotherm). The deep-layer mean wind, computed over the Doppler analysis domain, was 235° at 13 m s^{-1}. This is identical to the cell motion observed by the lower fuselage radar reflectivity. Removal of the deep-layer mean wind produced vertical wind cross sections reminiscent of those seen in many midlatitude and tropical squall lines. The vertical velocities derived from the Doppler analysis were as high as 15 to 20 m s^{-1} in the strongest convective cells.

Mean profiles of vertical velocity were computed from the two Doppler analysis domains. Each of these domains had an area of 250 km^2. The convective region mean vertical motion was positive at all altitudes > 1 km, with a maximum of 60 cm s^{-1} at 6 km altitude. The stratiform region's mean vertical motion showed a change from negative vertical velocities (about -20 cm s^{-1}) at < 4.5 km altitude (the height of the 0°C isotherm) to slightly positive values at altitudes > 4.5 km.

UW scientists completed an atlas of radar composites from the lower fuselage radar for all the EMEX cases and distributed them to interested parties.

Plans (FY-89)

HRD will continue its interaction with the UW group on the generation and interpretation of the pseudo-dual Doppler and vertical incidence analyses. HRD and UW will work to refine vertical velocity measurements from the vertical incidence data through improvements to the reflectivity-fall speed relationships for ice crystals.

12. A Climatological Study of the Atmosphere's Thermodynamic Structure

Goal

The spectral cloud ensemble model used in the Arakawa-Schubert cumulus parameterization scheme provides a general measure of the vertical thermodynamic structure and static stability of the atmosphere. In the tropics, it has been quite successful in quantifying the buoyant energy available to cumulus clouds (the cloud work function) and in predicting the cumulus precipitation over areas comparable to a grid box of a global model. The goal of this research is the application of this model to atmospheric regimes other than the tropics.

Accomplishments (FY-88)

Arakawa-Schubert work function statistics were calculated from data obtained earlier in a south Florida sea-breeze experiment. The means and standard deviations of the work function are similar to those in other regions, particularly those for the Venezuelan Meteorological and Hydrological Experiment. The statistical significance of these results has been established by a Monte Carlo technique. The diurnal change in thermodynamic structure is large and statistically significant.

Plans (FY-89)

A manuscript describing these results will be completed and submitted for publication.

13. Hurricane Energetics and Budget Study

Goal

This project is designed to measure the detailed kinematic and thermodynamic structure of a hurricane over a 240-nmi radius with Doppler radar and ODW's and to map the radar echo in three dimensions. These data will be used to compute the budgets of mass, total heat, water substance, kinetic energy, and absolute angular momentum.

Accomplishments (FY-88)

Previous budget studies of hurricanes were carried out in the early 1960's. Since that time, there have been significant advances in observing capabilities. These new capabilities, particularly the airborne Doppler radar and the ODW, now allow high-density and three-dimensional data coverage over a large volume of the hurricane that had been unattainable. The airborne Doppler radar provides the capability to measure the winds both in the outflow layer and in the boundary layer. The goal of the proposed experiment is to exploit these new tools to acquire data sets for the calculation of the budgets listed above.

The experimental and operational plan has been refined and published in the 1988 HRD Field Program Plan.

Plans (FY-89)

The experiment, which requires both P-3 aircraft to be equipped with airborne Doppler radar, will be carried out during the 1989 hurricane season if nature provides a suitable hurricane. The data set for Hurricane Gloria (1985) that is being analyzed in detail (project 6), will be used to attempt abbreviated budget analyses to test concepts and procedures.

14. Observational Studies of the South Florida Sea Breeze

Goal

The purpose of this project is improvement of the understanding of the sea breeze circulations that initiate much of the deep convection that forms during the afternoon over the Florida peninsula in summer. The research uses routine operational data archived at the National Climatic Center and P-3 aircraft observations that were obtained during HRD sea breeze experiments. The field phase of the sea breeze experiment was designed to provide a description of the mixed layer, cloud layer, and evolution of the sea breeze circulation from shortly after sunrise until midafternoon when deep convection is normally prevalent. The role of the sea breeze in organizing the development of deep convection is being examined. Airborne Doppler radar data were collected on two of the sea breeze experimental days and are being used to specify the kinematic structure of mesoscale precipitation lines that were initiated by the sea-breeze circulation.

Accomplishments (FY-88)

A study of July 23, 1987, was completed. This was a summer day in south Florida without significant rainfall or radar echoes. Such a day occurs < 1 day in 500. Normally, isolated cumulus clouds and organized areas of cumulus convection develop over the south Florida peninsula during the afternoon in response to the sea breeze circulation.

The lack of any significant rainfall in south Florida on July 23, 1987, was not caused by a failure of the sea breeze circulations to produce peninsula-scale convergence. The suppressed conditions were the result of an airmass with unusually low relative humidity at and above 850 mb. Nonprecipitating shallow cumulus clouds were able to form in some areas of south Florida. However, entrainment of the dry air prohibited deep cumulus clouds from developing. A stable layer near 850 mb may also have been a factor, but upward motion in the sea breeze convergence zones seemed capable of neutralizing or destabilizing this layer. The dry, stable airmass appears to have been a product of synoptic-scale subsidence on the east side of an anticyclone that dominated the eastern part of the United States.

On undisturbed summer days, the timing and location of deep convection in south Florida are controlled by the interaction between the sea breeze circulations and the prevailing synoptic-scale flow in the lower troposphere. When the sea breeze circulation is not weakened by extensive areas of opaque cloudiness, area-averaged rainfall varies by a factor of 50 from $\sim$ 0.3 to 14.0 mm d^{-1}. The area-averaged rainfall is significantly correlated with moisture and temperature in the middle troposphere and zonal wind speed in the lower troposphere. High moisture content, below-normal temperature, and weak zonal wind speed occur on days with above-average area rainfall. The variations of moisture, temperature, and zonal wind speed are largely determined by synoptic-scale weather systems.

The typical interaction between the sea breeze circulations and the prevailing synoptic-scale flow occurred on July 23, but the synoptically induced thermodynamic properties of the airmass dominated the peninsula-scale lifting in the sea breeze convergence zones; it either prevented air from reaching saturation or eroded the tops of shallow cumulus before sufficient depth was achieved for precipitation.

Plans (FY-89)

A short climatological study of the interaction between the lake breeze of Lake Okeechobee and the sea breeze circulations of the Florida peninsula will be started. Satellite pictures from 1986 and 1987 archived at NHC will be used to identify dominant patterns around Lake Okeechobee. The purpose of the study is identification of the thermodynamic and kinematic conditions that occasionally produce suppressed conditions downwind of the lake.

The results of the climatological study will be used to interpret the P-3 flights of July 14, 1982, when the two P-3's flew perpendicular to the coastline near Naples to monitor the development of the sea breeze circulation. The sea breeze circulation and deep convection failed to develop near Naples, however, as this area was affected by suppressed conditions downwind from Lake Okeechobee. Analyses of the aircraft data will be used to identify the reasons for the suppressed conditions.

COOPERATIVE RESEARCH PROJECTS

1. Desert Research Institute, University of Nevada

Principal Investigator: Dr. John Hallett

Project: The Ice Phase and Electrical Evolution in the Hurricane

Data from Hurricane Gilbert (1988) are being analyzed to assess the storm's electrical activity in relation to the eyewall. Results will be compared with data from Hurricanes Newton (1986) and Emily (1987).

A new instrument, a large-volume sampler for measuring particle charge, has been designed and fabricated. It is being mounted on the P-3 for testing. The instrument consists of an induction ring and an outer deiced shield. The ring, which is 6 inches in diameter, is able to detect particle charge down to 10^{-13} C. The innovative feature of this unit is its capability of real-time analysis of individual particle charge. Spurious charges that result from particle impaction are rejected by software. Net charge and numbers and sign of positive and negative charge particles can be displayed in near real time, recorded, and updated during flight.

The paper on the analysis of a convective cloud in a tropical environment has almost been completed. This is a unique observation by the P-3 in an isolated tower off Florida and demonstrates that, under some conditions, a Lagrangian study of a cloud element can be made by an aircraft rising at the same velocity as the element. The evolution of precipitation takes place within the cloud element, which enables the system to be considered as a near-isolated entity during the crucial stage of its evolution.

Related work. Further laboratory studies under National Science Foundation sponsorship have been carried out on particle break-up at the melting layer. These studies confirm the importance of environmental conditions on the break-up of particles. The break-up behavior is quite different in a dry layer, where evaporation is occurring, compared with melting in a layer close to water saturation (as in a hurricane). In the latter case, many ice particles are shed as melting occurs.

Related Publications

Oraltay, R. G., and J. Hallett, 1988: Melting and evaporation of ice crystals. *Prepr., 10th International Cloud Physics Conf.*-IAMAP-ICCP/WMO, Aug. 15-20, 1988, Bad Homburg, F.R.G., 22-24.

WILLIS, P. T., and J. Hallett: The development of precipitation near the top of a maritime convective tower. *J. Atmos. Sci.* (In preparation)

2. National Center for Atmospheric Research

Principal Investigators: Dr. Gary M. Barnes
Dr. Margaret A. LeMone

Project Scientists: Dr. Andrew J. Heymsfield
Mr. Gregory J. Stossmeister

Project: Hurricane Rainbands III: Mesoscale and Convective-Scale Structure

Hurricane Raymond (1983). G. Barnes, M. LeMone, and J. GAMACHE have been studying the kinematic structure of a convective cell in Hurricane Raymond (1983). The results were presented at the *International Conference on Tropical Meteorology.* The flow fields were derived using the airborne Doppler radar from two orthogonal flight tracks. This work shows the importance of the tangential wind in creating a convergence zone that is responsbie for the cellular reflectivity structure within the rainband. The stratiform region exists downband because the fall speeds of ice and snow are much less than the fall speeds of raindrops; not because of a stronger upper level relative flow. A paper on these analyses is in preparation for submission to the *Monthly Weather Review.*

Research related to other mesoscale phenomena. P. WILLIS and A. Heymsfield examined the evolution of particles above, through, and below the melting layer in the stratiform region of a mesoscale convective complex, which occurred on June 10 and 11, 1985, during PRE-STORM (Preliminary Regional Experiment - Stormscale Operational and Research Meteorology). They presented a paper on this study at the *10th International Cloud Physics Conference.* A manuscript that describes this study has been accepted by the *Journal of the Atmospheric Sciences.*

Tropical Storm Irma (1987). During EMEX, research flights were conducted in and around a rainband in Tropical Storm Irma (1987). B. Ryan (CSIRO), E. Zipser, and G. Barnes have begun analyses on this unusually wide rainband (50 km) to determine how the band evolved and how it might have affected development of the vortex.

Hurricane Gilbert (1988). G. Barnes and G. Stossmeister particpated in a research flight into Hurricane Gilbert on September 12, 1988. G. Barnes was the lead airborne mission scientist. He and P. BLACK developed the flight plans to study a strong rainband southeast of the circulation center. Despite a long ferry, interfering high terrain from nearby islands, and Cuban airspace complications, the flights of both NOAA P-3's were successfully executed for $\sim$ 4 h in and around the rainband. This was purported to be the most intense rainband studied to date.

Tropical Storm Isabel (1985). G. Stossmeister and G. Barnes are analyzing the data from the research flights into Tropical Storm Isabel (1985), which did not reach hurricane intensity. These flights concentrated on the mixed and lower cloud layers and convection with 200 km of the circulation center. The kinematic, thermodynamic, and reflectivity fields associated with Isabel will be contrasted with those of mature hurricanes to determine whether factors within the mesoscale convective system are responsible for the failure of Isabel to intensify.

Related Publications and Presentations

Barnes, G. M., M. A. LeMone, and J. F. GAMACHE, 1988: The structure and role of a convective cell in a hurricane rainband. *International Conference on Tropical Meteorology*-AMS/AMOS/CMS, July 4-8, 1988, Brisbane, Australia. (Presented)

Barnes, G. M., M. A. LeMone, J. F. GAMACHE, and G. J. Stossmeister: Convective cell structure in a hurricane rainband. *Mon. Weather Rev.* (In preparation)

Stossmeister, G. J., and G. M. Barnes, 1989: The inner core of nonintensifying Tropical Storm Isabel (1987). *Proc., 18th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 16–19, 1989, San Diego, Calif. (Accepted)

Ryan, B., G. M. Barnes, and E. J. Zipser, 1989: Rainband structure in developing Tropical Cyclone Irma (1987). *Proc., 18th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 16–19, 1989, San Diego, Calif. (Accepted)

WILLIS, P. T., and A. J. Heymsfield, 1988: Melting-layer structure in MCC stratiform precipitation. *Prepr., 10th International Cloud Physics Conf.*–AMS, August 15–20, 1988, Bad Homburg, F.R.G., 699–701.

WILLIS, P. T., and A. J. Heymsfield, 1989: Structure of the melting layer in MCS stratiform precipitation. *J. Atmos. Sci.* (Accepted)

3. State University of New York at Albany

Principle Investigator: Dr. Lance F. Bosart

Project Scientists: Mr. Joe Bartlo
Mr. Robert Weisman
Dr. Chung-Chieng Lai

Project: Synoptic- and Subsynoptic-Scale Diagnostic Studies of Tropical Convective Systems in Weakly Baroclinic Environments

Research is nearing completion on a diagnostic study of the evolution of the environmental structure accompanying the formation of Hurricane Diana east of Florida in September 1984. The results to date indicate a three-stage development process. First, a frontal wave forms east of Florida along an old frontal boundary in a weakly baroclinic environment. This formation occurs as a deep trough in the westerlies aloft reaches the East Coast. The second stage occurs as the southern end of the aforementioned trough separates from the main trough in the eastern Gulf of Mexico. Development of the frontal wave and incipient tropical storm formation occur on the western edge of the main cloud shield as a region of positive potential vorticity advection overspreads Florida. The maximum ascent occurs in the upper troposphere near 300 mb. Stage three, the transition to a hurricane, occurs in association with large-scale ridging to the north of the storm. This research is part of J. Bartlo's master's thesis work. C-C. Lai has provided computational assistance.

The southeast coastal Texas heavy rainstorm event of September 16–20, 1984, occurred in conjunction with favorable frontogenetical forcing in the midtroposphere. A cyclone disturbance formed just offshsore in the low-level easterlies, with the strongest winds of 25 m s^{-1} observed near 900 mb. Cold air damming east of the Mexican mountains contributed to enhanced baroclinity and convergence along the coast. C-C. Lai and R. Weisman helped with the analysis.

The principal investigator plans to present the important scientific findings at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in May, 1989, at San Diego, California. Papers describing the results will be submitted to the *Monthly Weather Review*.

4. State University of New York at Albany

Principal Investigator: Dr. John Molinari

Project Scientist: Mr. David Vollaro

Project: Synoptic-Scale Influences on Hurricane Intensity

We have examined the interaction of Hurricane Elena (1985) with a baroclinic wave and the effects of this interaction on hurricane intensity. The interaction is formulated from two points of view:

1) Computation of the radial flux of angular momentum by azimuthal eddies and inference of the radial-vertical response to this forcing using the balanced vortex approach of Eliassen.

2) Computation of isentropic potential vorticity evolution near tropopause level.

The hurricane outflow layer was analyzed using data from the international rawinsonde network and upper level cloud drift winds from the National Hurricane Center. Subsequently, the three-dimensional structure of the interaction was viewed using 2.5° latitude-longitude initialized analyses from the European Centre for Medium Range Weather Forecasts (ECMWF).

The angular momentum framework has provided a reasonably complete physical explanation for the major secondary deepening of Elena over water, given the eddy momentum forcing, as follows:

1) Due to the motion relative to the hurricane of a middle latitude trough in the upper troposphere, strong inward cyclonic momentum fluxes occurred, first several hundred kilometers from the core, later closer to the center. This eddy momentum forcing decayed rapidly below (and above) 200 mb, as is typical.

2) A clockwise gyre in the r-p plane occurred in response, with outflow aloft offsetting the inward momentum fluxes and inflow below spinning up the hurricane at middle levels.

3) Aircraft reconnaissance data from H. WILLOUGHBY show that, as the upper level forcing reached inner radii, there was formation of an outer wind maximum in the lower troposphere at r = 120 km.

4) This wind maximum shifted inward with time and was directly associated with the secondary deepening of Elena while it was over the Gulf of Mexico.

Thus, the inward cyclonic momentum fluxes produce intensification of the hurricane in a highly indirect manner. First, the mean vortex radial-vertical circulation was enhanced in response to the outflow layer eddy momentum sources, thus spinning up middle levels. Second, low levels spun up in the subsequent mass field response, in which mass was removed from the core to reestablish gradient balance at middle levels. Third, this response did not directly produce central pressure falls, but instead initiated an outer wind maximum, which, by reasonably well understood mechanisms, propagated inward and ultimately produced dramatic deepening. We view the latter process as evolving in the high Rossby number storm core, independent of the environment. The eddy momentum forcing would thus act as an external trigger to hurricane intensification, rather than as a direct mechanism. This description is consistent with the view of external forcing of tropical cylcones that was recently given by G. Holland.

The above is a physical sequence, given the momentum fluxes, but a complete dynamical interpretation must account for the three-dimensional evolution and the eddy flux variability. K. Emanuel noted that the approach of an upper level potential vorticity (PV) maximum (in this case, the midlatitude trough) within a deformation radius of a low-level PV maximum (the hurricane) will spin up the low-level circulation.

As an initial effort at a dynamical understanding, we have computed isentropic potential vorticity (IPV) from the ECMWF analyses after linearly interpolating u, v, and p to θ surfaces. Results from Elena at the θ = 350K level, which crosses from troposphere to stratosphere just north of the hurricane, show that the hurricane carves out a low IPV region at upper levels, presumably owing to diabatic destruction of IPV above the level of maximum heating. As proposed by Emanuel, an IPV maximum at upper levels, associated with the trough, shifts southward to just west of the hurricane core before the deepening of the storm. This result qualitatively suggests a dynamical mechanism for deepening, but further study will be required to understnd how the IPV field evolved, in particular, whether conservative or nonconservative processes were acting, and the nature of the interaction with the storm core. In addition, inversion of the potential vorticity field to obtain the wind and mass fields, while possible in principle, is extremely difficult in practice because of the complex balance relationship that must be assumed in the vicinity of the hurricane. As a result, we are also returning to the wind and mass fields for a physical understanding of the interaction between the trough and hurricane.

Related Publications and Abstracts

Molinari, J., and D. Vollaro, 1987: Evolution of the inflow and outflow layers of tropical cyclones prior to and during rapid pressure falls. *Ex. Abst., 17th Conf. on Hurricanes and Tropical Meteorology*-AMS, April 7-10, 1987, Miami, Fla., p. 270.

Molinari, J., and D. Vollaro, 1988: External influences on hurricane intensity: Part I. Outflow layer eddy angular momentum fluxes. *J. Atmos. Sci.* (Accepted)

Molinari, J., and D. Vollaro, 1988: External influences on hurricane intensity change. *International Conf. on Tropical Meteorology*-AMS/AMOS/CMS, July 4-8, 1988, Brisbane, Australia. (Presented).

Molinari, J., and D. Vollaro: External influences on hurricane intensity: Part II. Interaction with a baroclinic wave. *J. Atmos. Sci.* (In preparation)

Skubis, S., and J. Molinari, 1987: Angular momentum variation in a translating cyclone. *Quart. J. Roy. Meteorol. Soc.*, 113 (447), 1041-1048.

5. University of Chicago

Principal Investigator: Dr. T. Theodore Fujita

Project: Aerial and Ground Survey of Hurricane Damage

There were no landfalling hurricanes during 1988 that could be included in this study.

6. University of Massachusetts

Principal Investigator: Dr. Calvin T. Swift

Project Scientists: Ms. Karen St. Germain
Mr. Alan B. Tanner

Project: Microwave Remote-Sensing Measurements of Ocean Surface Winds in Hurricanes

This program uses an SFMR to remotely measure surface wind speed and rain rates in hurricanes. Last year, a rather detailed study concluded that the SFMR measures surface wind speed to an accuracy of $\pm$ 1.7 m s^{-1} for winds > 20 m s^{-1}. The SFMR was fabricated by the University of Massachusetts and has flown every year since 1984 on a NOAA P-3 aircraft. We consider the instrument to be operational for measuring high wind speed.

After the first flight of the sensor in 1984, a preliminary capability was developed to measure surface winds on a real-time basis. To this end, real-time remotely sensed surface winds were measured for the first time over Hurricane Gloria in 1985. Since then, work has been in progress to develop computer codes to derive real-time winds from the central computer on the P-3. It is expected that the program will be debugged in time for the 1989 hurricane season.

In September 1988, the SFMR was flown into Hurricane Gilbert and measured a surface wind speed of 155 kt, which is the highest oceanic surface wind speed ever measured by any method.

Our future activity will be to guide the SFMR to operational status.

Related Publications

BLACK, P. G., and C. T. Swift, 1984: Airborne stepped-frequency microwave radiometer measurements of rain rate and surface wind speeds in hurricanes. *Proc., 22nd Conf. on Radar Meteorology*-AMS, September 10-14, 1984, Zurich, Switzerland, 433-438.

Jones, W. L., P. G. BLACK, V. E. Delnore, and C. T. Swift, 1981: Airborne microwave remote-sensing measurements of Hurricane Allen. *Science*, 214 (4528), 274-280.

Tanner, A., C. T. Swift, and P. G. BLACK, 1987: Operational airborne remote sensing of wind speeds in hurricanes. *Ext. Abs., 17th Conf. on Hurricanes and Tropical Meteorology*-AMS, April 7-10, 1987, Miami, Fla., 385-387.

Tanner, A., C. T. Swift, and P. G. BLACK: Airborne microwave spectral radiometer measurements of surface wind speed and rain rate in hurricanes. *J. Atmos. Oceanic Tech.* (In preparation)

7. University of Washington

Principal Investigator: Dr. Robert A. Houze, Jr.

Project Scientists: Messrs. Brian Mapes, Michael Biggerstaff, Dean Churchill, Stephen Bograd, and Chungli Wang

HRD Co-Investigators: Dr. Frank D. Marks, Jr., Dr. John F. Gamache, and Mr. Robert A. Black

Project: Analysis of AOML/HRD P-3 Doppler Radar Data

Continuing progress has been made on the analysis of airborne Doppler radar data in Hurricane Norbert (1984) and EMEX. The three-dimensional wind field in the entire inner region of Huricane Norbert has been synthesized and analyzed in terms of meaningful kinematic components. The ice particle data collected throughout the inner region have been analyzed in the context of the derived motion fields. The water budget of the inner region has been diagnosed from a combination of the radar reflectivity and Doppler radar wind fields. Preliminary results were presented at the *10th International Cloud Physics Conference* in August 1988. Manuscripts are in preparation.

A color atlas of the composite radar reflectivity patterns observed with the lower fuselage radar during the 10 EMEX missions has been compiled and distributed. The vertical distributions of reflectivity observed with the tail radar have been examined in all of the plots and a master's thesis by S. J. Bograd will describe the results. Software has been developed at the University of Washington to edit, interpolate, and synthesize the airborne Doppler radar data collected in EMEX. For his Ph.D. research, B. Mapes is developing and applying several techniques to determine vertical motion profiles from the Doppler data from single Doppler and pseudo-dual Doppler scans for all the EMEX flights. For her master's thesis research, C. Wang is applying pseudo-dual Doppler techniques to data from several flights to derived vertical air motions.

Related Publications

GAMACHE, J. F., R. W. BURPEE, and F. D. MARKS, JR., 1987: Equatorial Mesoscale Experiment (EMEX) data inventory. NOAA, AOML/HRD, Miami, Fla., 120 pp.

GAMACHE, J. F., F. D. MARKS, JR., R. A. BLACK, and R. A. Houze, Jr., 1988: The bulk water budget of Hurricane Norbert (1984) as determined from thermodynamic and microphysical analyses retrieved from airborne Doppler radar. *Prepr., 10th International Cloud Physics Conf.,Vol. II–* IAMAP–ICCP/WMO, Aug. 15–20, 1988, Bad Homburg, F.R.G., 711–713.

Houze, R. A., Jr., 1988: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteorol. Soc.* (In press)

Houze, R. A., Jr., 1988: Convective and stratiform precipitation in the tropics. *Proc., International Symposium on Tropical Precipitation Measurements*, Tokyo, Japan. (In press)

Houze, R. A., Jr., S. J. Bograd, and B. Mapes, 1988: An atlas of horizontal patterns of radar reflectivity observed during EMEX aircraft missions. Dept. of Atmos. Sci., Univ. of Washington, Seattle, WA, 98195.

Houze, R. A., Jr., F. D. MARKS, JR., and R. A. BLACK, 1988: Mesoscale patterns of ice particle characteristics in Hurricane Norbert. *Prepr., 10th International Cloud Physics Conf., Vol. II–* IAMAP–ICCP/WMO, Aug. 15–20, 1988, Bad Homburg, F.R.G., 708–710.

Houze, R. A., Jr., F. D. MARKS, JR., and R. A. BLACK: Dual aircraft investigation of the inner core of Hurricane Norbert: Part II, Patterns of fallout and growth of ice particles. *J. Atmos. Sci.* (In preparation)

MARKS, F. D., JR., 1987: EMEX research aircraft plan. NOAA, AOML/HRD, Miami, Fla., 50 pp.

MARKS, F. D., JR., and R. A. Houze, Jr., 1987: Three-dimensional structure of the eyewall of Hurricane Norbert as determined from an airborne Doppler radar. *Ex. Abs., 17th Conference on Hurricanes and Tropical Meteorology*-AMS, April 7-10, 1987, Miami, Fla., 347-350.

MARKS, F. D., JR., R. A. Houze, Jr., and J. F. GAMACHE: Dual aircraft investigation of the inner core of Hurricane Norbert: Part I, Kinematic and thermodynamic structure. *J. Atmos. Sci.* (In preparation)

Appendix A: Publications[5]

A.1 In Print

[1] BLACK, P. G., 1988: Hurricane–ocean interaction near the subtropical front. *7th Conf. on Ocean–Atmosphere Interaction*–AMS, Jan. 31–Feb. 5, 1988, Anaheim, Calif., J60.

[2] BLACK, P. G., R. L. Elsberry, and L. K. Shay, 1988: Airborne surveys of ocean current and temperature perturbations induced by hurricanes. *Advances in Underwater Technology, Ocean Science and Offshore Engineering*, Vol. 16, Oceanology '88. Graham & Trotman, London, 51–58.

[3] BLACK, P. G., R. L. Elsberry, L. K. Shay, R. M. Partridge, and J. Hawkins, 1988: Atmospheric boundary–layer and oceanic mixed–layer observations in Hurricane Josephine obtained from air–deployed drifting buoys and research aircraft. *J. Atmos. & Oceanic Tech.*, 5 (6).

[4] Bluestein, H. B., and F. D. MARKS, JR., 1987: On the structure of the eyewall of Hurricane Diana (1984): Comparison of radar and visual characteristics. *Mon. Weather Rev.*, 115 (10), 2542–2552.

[5] BURPEE, R. W., 1988: Forecaster biography. Grady Norton – Hurricane forecaster extraordinaire. *Wea. & Forecast.*, 3 (3), 247–254.

[6] DeMARIA, M., 1987: Tropical cyclone track prediction with a barotropic spectral model. *Mon. Weather Rev.*, 115 (10), 2346–2357.

[7] DeMARIA, M., 1988: The effect of physical processes on the convergence of Machenhauer's normal mode initialization scheme. *8th Conf. on Numerical Weather Prediction*–AMS, Feb. 22–25, 1988, Baltimore, Md., 751–757.

[8] DeMARIA, M., and J. D. Pickle, 1988: A simplified system of equations for simulation of tropical cyclones. *J. Atmos. Sci.*, 45 (10), 1542–1554.

[9] DODGE, P. P., 1987: A climatology of rainbands observed by coastal radars in GALE. *Reports of GALE/CASP Preliminary Analysis Workshop*, Nov. 3–5, 1987, Virginia Beach, Va., 19–22.

[10] FRANKLIN, J. L., and S. J. LORD, 1988: Comparisons of VAS and Omega dropwindsonde thermodynamic data in the environment of Hurricane Debby (1982). *Mon. Weather Rev.*, 116 (8), 1690–1701.

[11] FRANKLIN, J. L., S. J. LORD, and F. D. MARKS, JR., 1988: Dropwindsonde and radar observations of the eye of Hurricane Gloria (1985). *Mon. Weather Rev.*, 116 (5), 1237–1244.

[12] GAMACHE, J. F., F. D. MARKS, JR., R. A. BLACK, and R. A. Houze, Jr., 1988: The bulk water budget of Hurricane Norbert (1984) as determined from thermodynamic and microphysical analyses retrieved from airborne Doppler radar. *Prepr., 10th International Cloud Physics Conf.*, Vol. II–IAMAP–ICCP/WMO, Aug. 15–20, 1988, Bad Homburg, F.R.G., 711–713.

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[5]HRD authors' names are in capital letters.

[13] Houze, R. A., Jr., S. J. Bograd, and B. Mapes, 1988: An atlas of horizontal patterns of radar reflectivity observed during EMEX aircraft missions. Research supported by NOAA Grant 40-WCNR-6-02428. Dept. of Atmos. Sci., Univ. of Washington, Seattle, WA, 98195.

[14] Houze, R. A., Jr., F. D. MARKS, JR., and R. A. BLACK, 1988: Mesoscale patterns of ice particle characteristics in Hurricane Norbert. *Prepr., 10th International Cloud Physics Conf.*-IAMAP-ICCP/WMO, Aug. 15-20, 1988, Bad Homburg, F.R.G., 708-710.

[15] JONES, R. W., 1987: A simulation of hurricane landfall with a numerical model featuring latent heating by the resolvable scales. *Mon. Weather Rev.*, 115 (10), 2279-2297.

[16] LORD, S. J., 1987: The 17th Conference on Hurricanes and Tropical Meteorology, 7-10 April 1987, Miami, Florida. *Bull. Amer. Metorol. Soc.*, 68 (11), 1431-1437.

[17] LORD, S. J., and J. L. FRANKLIN, 1987: The environment of Hurricane Debby (1982). Part I: Winds. *Mon. Weather Rev.*, 115 (11), 2760-2780.

[18] LORD, S. J., and J. L. FRANKLIN, 1988: Diagnostics of thermodynamic and wind fields in the environment of Hurricane Debby (1982). *Prepr., 8th Conf. on Numerical Weather Prediction*-AMS, Feb. 22-25, 1988, Baltimore, Md., 605-610.

[19] LORD, S. J., and J. M. LORD, 1988: Vertical velocity structures in an axisymmetric, nonhydrostatic tropical cyclone model. *J. Atmos. Sci.*, 45 (9), 1453-1461.

[20] OOYAMA, K. V., 1987: Scale-controlled objective analysis. *Mon. Weather Rev.*, 115 (10), 2479-2506.

[21] Oraltay, R. G., and J. Hallett, 1988: Melting and evaporation of ice crystals. Research supported by NOAA Grant 40-WCNR-8-01406. *Prepr., 10th International Cloud Physics Conf.*-IAMAP-ICCP/WMO, Aug. 5-20, 1988, Bad Homburg, F.R.G., 22-24.

[22] POWELL, M. D., 1988: Boundary-layer structure and dynamics in outer hurricane rainbands. Ph.D. dissertation, Dept. of Meteorology, Florida State University, Tallahassee, 277 pp.

[23] POWELL, M. D., and P. Georgiou, 1987: Response of the Allied Bank Plaza Tower during Hurricane Alicia (1983). *J. Wind Engineering and Industrial Dynamics*, 26, 231-254.

[24] Sanford, T. B., P. G. BLACK, J. R. Haustein, J. W. Feeney, G. Z. Forristall, and J. F. Price, 1987: Ocean response to a hurricane. Part I - Observations. *J. Phys. Oceanog.*, 17 (11), 2065-2083.

[25] SHAPIRO, L. J., 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Weather Rev.*, 115 (11), 2598-2614.

[26] SHAPIRO, L. J., D. E. Stevens, and P. E. Ciesielski, 1988: A comparison of observed and model-derived structures of Caribbean easterly waves. *Mon. Weather Rev.*, 116 (4), 921-938.

[27] Skubis, S., and J. Molinari, 1987: Angular momentum variation in a translating cyclone. Research supported by NOAA Grant 50-WCNR-6-06096. *Quart. J. Roy. Meteorol. Soc.*, 113 (477), 1041-1048.

[28] WILLIS, P. T., and A. J. Heymsfield, 1988: Melting layer structure in MCC stratiform precipitation. *Prepr., 10th International Cloud Physics Conf.*-IAMAP-ICCP/WMO, Aug. 15-20, 1988, Bad Homburg, F.R.G., 699-701.

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A.2 Accepted

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[64] WILLIS, P. T., and A. J. Heymsfield, 1989: Structure of the melting layer in MCS stratiform precipitation. *J. Atmos. Sci.*

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[69] DeMARIA, M., J. M. Davis, and D. M. Wojtak: Observations of mesoscale wave disturbances during the Genesis of Atlantic Lows Experiment. *Mon. Weather Rev.*

[70] DeMARIA, M., M. B. Lawrence, and J. T. Kroll: An error analysis of Atlantic tropical cyclone track guidance models. *Wea. & Forecast.*

[71] Holland, G., and P. G. BLACK: Boundary-layer dynamics in Hurricane Kerry (1979): Part I - Mesoscale structure. *J. Atmos. Sci.*

[72] SHAPIRO, L. J.: The relationship of the quasi-biennial oscillation to Atlantic tropical storm activity. *Mon. Wea. Rev.*

[73] Shay, L. K., R. L. Elsberry, and P. G. BLACK: Vertical structure of the ocean current response to hurricanes. *J. Phys. Oceanogr.*

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[74] Barnes, G. M., M. A. LeMone, J. F. GAMACHE, and G. J. Stossmeister: Convective cell structure in a hurricane rainband. Research supported by NOAA Grant 45-WCNR-5-00388. *Mon. Weather Rev.*

[75] BLACK, P. G.: Observed ocean response to tropical cyclones, I: Sea surface temperature patterns induced by fast-moving storms. *J. Phys. Oceanogr.*

[76] BURPEE, R. W., and M. L. BLACK: Temporal and spatial variations of rainfall near the centers of two tropical cyclones. *Mon. Weather Rev.*

[77] FRIEDMAN, H. A., and E. M. Ressler: A Resource Guide for U. N. Members of Tropical-Cyclone-Prone Regions. World Meteorological Organization Tropical Cyclone Programme No. 14: "Public Information and Education." World Meteorological Organization (WMO), Office of the U. N. Disaster Relief Co-ordinator (UNDRO), and the League of Red Cross Societies (LRCS), Geneva, Switzerland.

[78] GAMACHE, J. F.: Microphysical observations in summer MONEX clouds. *Mon. Weather Rev.*

[79] GAMACHE, J. F.: A method for correcting the ambient temperature measurement by the side-looking PRT-5 radiometer aboard the NOAA P-3 aircraft. *J. Atmos. Oceanic Tech.*

[80] Goldenberg, S. B., S. D. ABERSON, and R. E. KOHLER: Incorporation of Omega dropwindsonde and storm-influenced wind into an operational barotropic hurricane-track forecast model. *Mon. Weather Rev.*

[81] Houze, R. A., Jr., F. D. MARKS, JR., and R. A. BLACK: Dual aircraft investigation of the inner core of Hurricane Norbert: Part II, Patterns of fallout and growth of ice particles. Research supported by NOAA Grant 50-WCNR-8-06088. *J. Atmos. Sci.*

[82] MARKS, F. D., JR., R. A. Houze, Jr., and J. F. GAMACHE: Dual aircraft investigation of the inner core of Hurricane Norbert: Part I, Kinematic and thermodynamic structure. *J. Atmos. Sci.*

[83] Molinari, J., and D. Vollaro: External influences on hurricane intensity: Part II. Interaction with a baroclinic wave. Research supported by NOAA Grant 50-WCNR-8-06088. *J. Atmos. Sci.*

[84] POWELL, M. D.: Boundary-layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale rainfall and kinematic structure. *Mon. Weather Rev.*

[85] POWELL, M. D.: Boundary-layer structure and dynamics in outer hurricane rainbands. Part II: Thermodynamic structure, downdraft modification, and mixed-layer recovery. *Mon. Weather Rev.*

[86] POWELL, M. D., and P. G. BLACK: Estimating oceanic surface winds in hurricanes: Relationships between NOAA aircraft reconnaissance and buoy platforms. *Mon. Weather Rev.*

[87] SHAPIRO, L. J.: The relationship of the QBO to Atlantic tropical storm activity. *Mon. Weather Rev.*

[88] Tanner, A., C. T. Swift, and P. G. BLACK: Airborne microwave spectral radiometer measurements of surface wind speed and rain rate in hurricanes. *J. Atmos. Oceanic Tech.*

[89] WILLIS, P. T.: The morphology of hydrometeors in a melting layer. *J. Atmos. Sci.*

[90] WILLIS, P. T., and J. Hallett: The development of precipitation near the top of a maritime convective tower. *J. Atmos. Sci.*

[91] WILLOUGHBY, H. E.: Gradient balance in tropical cyclones. *J. Atmos. Sci.*

[92] WILLOUGHBY, H. E.: Temporal changes of the primary circulation in tropical cyclones. *J. Atmos. Sci.*

Appendix B: Presentations[6]

B.1 AOML Seminars Presented by HRD Staff and Visitors

1988

February 17	Dr. Julian McCreary (Nova University): "The Ocean Response to Strong Offshore Forcing by Mountain-Pass Wind Jets: Model Results"
March 10	Dr. MARK DEMARIA: "Predictability of Tropical Cyclone Motion"
March 21	Professor Larry Mahrt (Oregon State University): "Limit Cycle Mixing"
March 25	Dr. John Lewis (NOAA/National Severe Storms Laboratory): "GUFMEX: Return Flow in the Gulf of Mexico"
April 11	Dr. PETER G. BLACK: "Airborne Surveys of Ocean Currents and Temperature Perturbations Induced by Hurricanes"
April 28	Dr. Lynn K. Shay (U. S. Naval Postgraduate School): "Vertical Structure of the Ocean Current Response to Hurricanes"
May 4	Dr. Gary M. Barnes (National Center for Atmospheric Research): "Updraft Structure Observed at Cloud Base"
May 26	Dr. Edward J. Walsh (NASA): "Directional Wave Spectrum Measurements With the Surface Contour Radar"
May 27	Mr. Eugene W. McCaul, Jr. (University of Oklahoma): "Hurricane-Spawned Tornadoes" (CIMAS Seminar Series)
June 7	Dr. Hartmut Kapitza (University of Oklahoma and GKSS Research Center, F.R.G.): "A Conjugate Gradient Poisson Solver for a Nonhydrostatic Mesoscale Meteorological Model"
June 8	Dr. Chung-Hsiung Sui (University of Maryland): "Westerly Wind Burst and Air-Sea Interaction Over the Equatorial Pacific Ocean" (CIMAS Seminar Series)
June 10	Dr. Dieter Eppel (GKSS Research Center, F.R.G.): "Mesoscale Modeling at GKSS Research Center"
July 27	Dr. Noel Davidson (Florida State University - Visiting Scientist): "Tropical Cyclone Genesis During the Australian Monsoon Experiment" (CIMAS Seminar Series)
August 9	Mr. Richard E. Carbone (National Center for Atmospheric Research): "Observations and Numerical Simulations on the Forcing of a Nocturnal Midwestern Squall Line" (CIMAS Seminar Series)
August 15	Mr. Richard E. Carbone (National Center for Atmospheric Research): "Observing Facilities at NCAR: Present and Future" (CIMAS Seminar Series)

[6]HRD speakers' names are in capital letters.

AOML Seminars (Continued)

August 23	Mr. Richard E. Carbone (National Center for Atmospheric Research): "Numerical Simulations" (CIMAS Seminar Series)
August 24	Dr. John Molinari (State University of New York/Albany): "Environmental Interactions and Tropical Cyclone Intensity"
August 29	Mr. Richard E. Carbone (National Center for Atmospheric Research): "The Hawaiian Rainband Experiment" (CIMAS Seminar Series)
August 30	Professor Roger Wakimoto (University of California at Los Angeles): "Non-Supercell Tornadoes"
August 31	Dr. James Leise (NOAA/Office of Aircraft Operations): "Overview of OAO P-3 Processing Upgrade"
October 6	Mr. Takashi Oshima (Meteorological Satellite Center, Tokyo): "Estimation of Ocean Surface Wind for a Typhoon from GMS Cloud Motion Winds"
October 13	Mr. Jeff Masters (NOAA/Office of Aircraft Operations): "Navigational Problems on NOAA's P-3 Aircraft"

B.2 AOML Informal Research Reports Presented by HRD Staff

1987

November 3	Dr. MARK D. POWELL: "Boundary-Layer Structure in the Vicinity of Outer Convective Hurricane Rainbands"
November 17	Dr. STEPHEN J. LORD: "Recent Studies Using the Arakawa-Schubert Cumulus Parameterization (Florida Sea Breeze; Hurricane Debby, 1982)"

1988

January 19	Dr. FRANK D. MARKS, JR.: "Kinematic Structure of the Inner Core of Hurricanes Norbert and Gloria as Viewed by Airborne Doppler Radar"
March 8	Mr. PAUL T. WILLIS: "A Proposed Hurricane Energetics Experiment"
March 15	Dr. LLOYD J. SHAPIRO: "The Relationship of the Quasi-Biennial Oscillation to Atlantic Tropical Storm Activity"
March 29	Dr. HUGH E. WILLOUGHBY: "Temporal Evolution of the Primary Circulation in Atlantic Hurricanes"
April 6	Dr. KATSUYUKI V. OOYAMA: "A New Design for Numerical Models of the Moist Atmosphere"
May 17	Dr. ROBERT W. BURPEE: "A Summer Day Without Significant Convection in South Florida"
June 14	Dr. JOHN F. GAMACHE: "Hurricane Norbert (1984): Water Budget Computations"
June 21	Dr. MARK DEMARIA: "Application of Normal Mode Initialization to Tropical Cyclone Modeling"

B.3 HRD Seminars

1987

October 1	Dr. KATSUYUKI V. OOYAMA: "Wave-CISK"
May 11	Dr. MARK D. POWELL: "Boundary-Layer Structure and Dynamics in Outer Hurricane Rainbands"

B.4 HRD Informal Research Reports

1987

October 26	Mr. PETER P. DODGE: "Climatology of GALE Rainbands"
November 23	Mr. ROBERT A. BLACK: "Comparisons of Radar Reflectivity and 2-D Particle Image Data in Two Atlantic Hurricanes"

1988

April 4	Mr. VICTOR WIGGERT: "Storm Surge: The SLOSH Model for the Florida Keys and Florida Bay"
May 9	Mr. JAMES L. FRANKLIN: "Preliminary Wind Analyses for Hurricane Josephine (1984)"
May 25	Mr. MICHAEL L. BLACK: "Rainbands in Hurricane Elena (1985)"
June 13	Mr. JOHN KAPLAN: "Comparison of ODW and Satellite Data"

B.5 Presentations Given Outside by HRD Staff

1987

November 10	Dr. HUGH E. WILLOUGHBY: "Motion of a Shallow Water Hurricane-Like Vortex" (at Florida State University)
November 16	Dr. LLOYD J. SHAPIRO: "Observed and Model-Derived Structures of Caribbean Easterly Waves" (at Massachusetts Institute of Technology)

1988

March 2	Dr. LLOYD J. SHAPIRO: "Impact of Climate Change on Hurricanes" (Invited report to Task Team on Implications of Climatic Changes in the Wider Caribbean Region, U.N. Environment Program)
March 18	Dr. PETER G. BLACK: "Boundary-Layer Wind Profiles" (1988 WMO Training Course on Tropical Meteorology and Tropical Cyclone Forecasting)
March 18	Dr. HUGH E. WILLOUGHBY: "Concentric Eyes in Hurricanes" (1988 WMO Training Course on Tropical Meteorology and Tropical Cyclone Forecasting)

Presentations Outside (Continued)

March 18	Dr. FRANK D. MARKS, JR.: "Doppler Radar Presentations in Hurricanes" (1988 WMO Training Course on Tropical Meteorology and Tropical Cyclone Forecasting)
April 8	Dr. FRANK D. MARKS, JR.: "Kinematic Structure of the Inner Core of Hurricane Norbert" (at Massachusetts Institute of Technology)
April 12	Dr. ROBERT W. BURPEE: "Flying into the Eye of a Hurricane" (at MIT Club of Palm Beach County)
April 28	Dr. FRANK D. MARKS, JR.: "Kinematics of the Inner Core of Hurricanes Norbert and Gloria" (at University of Washington)
May 17	Dr. MARK D. POWELL: "Boundary-Layer Structure and Dynamics in Outer Hurricane Rainbands" (at Florida State University)
May 18	Dr. PETER G. BLACK: "Airborne Surveys of Ocean Current and Temperature Perturbations Induced by Hurricanes" (at Florida State University)
May 31	Dr. STEPHEN J. LORD: "Wind and Thermodynamic Analyses of the Hurricane Environment" (at Florida State University)
June 26	Mr. HOWARD A. FRIEDMAN: "What's Behind That Cold Front?" (Festival of Life Enrichment Series/QE 2)
June 27	Mr. HOWARD A. FRIEDMAN: "Atmospheric Sciences: More Than Just Forecasting" (Festival of Life Enrichment Series/QE 2).
July 4	Mr. HOWARD A. FRIEDMAN: "Atmospheric Sciences: More Than Just Forecasting" (Festival of Life Enrichment Series/QE 2).
July 5	Mr. HOWARD A. FRIEDMAN: "What's Behind That Cold Front?" (Festival of Life Enrichment Series/QE 2)
July 8	Mr. HOWARD A. FRIEDMAN: "National Weather Service Forecast Products for Mariners" (at Shelter Island Yacht Club, N.Y.)
July 9	Mr. HOWARD A. FRIEDMAN: "Hurricanes" (at Shelter Island Yacht Club, N.Y.)
July 20	Dr. KATSUYUKI V. Ooyama: "'Primitive' Thermodynamics for Modeling the Moist Atmosphere" (at NOAA/National Meteorological Center)
July 21	Dr. ROBERT W. BURPEE: "P-3 Reconnaissance Data for the National Hurricane Center in the 1990's" (at NWS/National Hurricane Center)
July 21	Dr. JOHN F. GAMACHE: "Thermodynamic Retrieval in Hurricane Norbert" (at NWS/National Hurricane Center)
July 21	Dr. FRANK D. MARKS, JR.: "Kinematics of the Hurricane Inner Core From Airborne Doppler Observations" (at NWS/National Hurricane Center)
July 21	Dr. MARK D. POWELL: "Hurricane Boundary-Layer Structure in the Vicinity of Well-Organized Outer Rainbands" (at NWS/National Hurricane Center)

Presentations Outside (Continued)

July 21	Mr. PAUL T. WILLIS: "Plans for the 1988 Hurricane Energetics and Budgets Study" (at NWS/National Hurricane Center)
July 21	Dr. HUGH E. WILLOUGHBY: "Dynamics of the Hurricane Inner Core" (at NWS/National Hurricane Center)
July 28	Mr. ROBERT A. BLACK: "(a) Vertical Winds in Hurricane Emily; (b) Reflectivity-Mass Relationships in Stratiform Ice Regions of Hurricane Norbert" (at NOAA/Office of Aircraft Operations)
July 28	Dr. ROBERT W. BURPEE: "P-3 Reconnaissance Data for the National Hurricane Center in the 1990's" (at NOAA/Office of Aircraft Operations)
July 28	Dr. JOHN F. GAMACHE: "Thermodynamic Retrieval in Hurricane Norbert" (at NOAA/Office of Aircraft Operations)
July 28	Dr. FRANK D. MARKS, JR.: "Kinematics of the Hurricane Inner Core From Airborne Doppler Observations" (at NOAA/Office of Aircraft Operations)
July 28	Dr. MARK D. POWELL: "Hurricane Boundary-Layer Structure in the Vicinity of Well-Organized Outer Rainbands" (at NOAA/Office of Aircraft Operations)
July 28	Dr. HUGH E. WILLOUGHBY: "Dynamics of the Hurricane Inner Core" (at NOAA/Office of Aircraft Operations)

B.6 Special Presentations

AOML/CIMAS Program Review

April 20, 1988

Dr. S. L. ROSENTHAL	"Hurricane Research Overview"
Dr. R. W. BURPEE	"Hurricane Field Program: Accomplishments and Plans"
Dr. S. J. LORD	"Research and Real-Time Analysis of the Tropics and the Hurricane Environment"
Mr. J. L. FRANKLIN	"Comparison of VAS and Omega Dropwindsonde Data"
Dr. H. E. WILLOUGHBY	"Monitoring Hurricane Motion and Development"
Dr. P. G. BLACK	"Hindcasting Surface Winds in Hurricane Floyd and TD #2"
Dr. F. D. MARKS, JR.	"Kinematic and Microphysical Structure of the Inner Core of Hurricane Norbert"
Dr. L. J. SHAPIRO	"The Relationship of Atlantic Tropical Storm Activity to the Tropical Circulation"

Special Presentations (Continued)

Dr. K. V. OOYAMA	"Modeling the Hurricane in Multiscale Geometry and Physics"
Dr. M. DEMARIA	"Barotropic Hurricane Track Forecasting Using the SAFER Method"

Presentations to P.R.C. Visiting Scientists

June 3, 1988

Dr. S. L. ROSENTHAL	"Introduction to AOML/HRD"
Mr. J. L. FRANKLIN	"Comparison of VAS and Omega Dropwindsonde Data"
Dr. S. J. LORD	"Research and Real-Time Analysis of the Tropics and the Hurricane Environment"
Dr. M. DEMARIA	"Barotropic Hurricane Track Forecasting Using the SAFER Method"
Mr. J. W. TROUT	"AOML Computer Facilities"

B.7 Unpublished[7] Conference Presentations

24th Annual NOAA/NWS Hurricane Conference

December 1-3, 1987, Coral Gables Florida

Dr. P. G. BLACK	"A Comparison of Storm-Relative Surface Observations With NOAA Reconnaissance Flight-Level Observations in Floyd"
Mr. J. L. FRANKLIN	"Dropwindsonde and Radar Observations of the Eye of Hurricane Gloria (1985)"
Dr. S. J. LORD	"Results of Real-Time Wind Analyses in the Environments of Hurricane Emily and Tropical Storm Floyd"
Dr. S. L. ROSENTHAL	"The Evolution of HRD's Applied Research Program"
Dr. H. E. WILLOUGHBY	"Status of Real-Time Hurricane Data Analysis"
Dr. H. E. WILLOUGHBY	"Expanded Data Transmission From Research Aircraft"

[7]Published conference reports are listed in section A.1.

42nd Annual Interdepartmental Hurricane Conference

Research Committee Meeting, January 12, 1988,

Homestead AFB, Florida

Dr. P. G. BLACK	"A Comparison of Surface and Flight-Level Observations in TD #2 With Those in Hurricane Floyd"
Mr. J. L. FRANKLIN	"Comparisons of VAS and Omega Dropwindsonde Thermodynamic Data in the Environment of Hurricane Debby (1982)"
Dr. F. D. MARKS, JR.	"Kinematic Structure of the Inner Core of Hurricanes Norbert and Gloria as Viewed by Airborne Doppler Radar"
Dr. M. D. POWELL	"The Relationship of Hurricane Reconnaissance Flight-Level Wind Measurements to Winds Measured by NOAA's Oceanic Platforms"
Dr. H. E. WILLOUGHBY	"Status of Real-Time Hurricane Data Analysis"

Annual Meeting of the AMS Board on School and

Popular Meteorological and Oceanographic Education (BSPMOE),

February 1-2, 1988, Anaheim, California

Mr. H. A. FRIEDMAN

a) "BSPMOE-Related Activities in 1987 and Plans for 1988"
b) "Sky Education in Boston"
c) "NOAA's Cooperative Education Program"
d) "Marine and Atmospheric Science Programs in Dade County (Florida) Public Schools"
e) "The Everyday Weather Project: A Program Developed at SUNY/College at Brockport, N.Y."
f) "Annual Report of the BSPMOE-AMS"

10th Annual National Hurricane Conference

April 5-8, 1988, Atlanta, Georgia

Dr. P. G. BLACK	"New Techniques for Providing Improved Wind Estimates in the Habitation Layer" (at Workshop Session on "Meteorological Aspects of the Hurricane Warning System")

Unpublished Conference Presentations (Continued)

International Conference on Tropical Meteorology–AMS/AMOS/CMS,

July 4–8, 1988, Brisbane, Australia

Dr. G. M. Barnes, Dr. M. A. LeMone, and Dr. J. F. GAMACHE	"The Structure and Role of a Convective Cell in a Hurricane Rain-band"
Dr. P. G. BLACK	"The Effect on Tropical Cyclone Surface Fluxes of Superposing Sea–Surface Temperature and Theta–E Perturbations"
Dr. R. W. BURPEE, Mr. M. L. BLACK, and Mr. P. P. DODGE	"Hurricane Precipitation Patterns Recorded by Land–Based Radar"
Dr. S. J. LORD	"The Inner Core Structure of Hurricane Gloria (1985) as Revealed by Airborne Doppler Radar"
Dr. F. D. MARKS, JR. and Dr. R. A. Houze, Jr.	"Mesoscale Organization of Cloud Clusters Observed in EMEX"
Dr. J. Molinari and Mr. D. Vollaro	"External Influences on Hurricane Intensity Change"
Dr. M. D. POWELL	"Boundary–Layer Structure in Convective Tropical Cyclone Rain-bands"
Dr. L. J. SHAPIRO	"The Relationship of the Quasi–Biennial Oscillation to Atlantic Tropical Storm Activity"
Dr. H. E. WILLOUGHBY	"The Dynamics, Structure, and Evolution of the Tropical–Cyclone Vortex Core"

B.8 Workshop Participation[8]

Battan Memorial and 40th Anniversary Meeting and Workshop

on Radar Meteorology–AMS, November 9–13, 1987,

Boston, Massachusetts

Dr. F. D. MARKS, JR. and Dr. P. G. BLACK	Panel: "Mobile Platforms"
Mr. P. T. WILLIS	Panel: "Cloud Microphysics and Radar"

Hurricane Analysis Workshop–NMC

December 15–16, 1987, Washington, D.C.

Dr. R. W. BURPEE and Dr. K. V. OOYAMA	"Overview of Hurricane Research at HRD"
Dr. R. W. BURPEE	"Dropwindsonde Data"
Dr. S. J. LORD	"Analysis of the Tropical Cyclone Environment of Several Atlantic Storms (1982–1987)"

STORM Community Workshop–ERL

July 25–28, 1988, Longmont, Colorado

Dr. R. W. BURPEE

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[8]Published workshop papers are listed in section A.1.

Appendix C: Staff Activities

C.1 Committee Memberships and Offices in Scientific Organizations

Mr. MICHAEL L. BLACK	Vice-Chairman, Miami Chapter, American Meteorological Society
Dr. PETER G. BLACK	Member, Air-Sea Interaction Committee, American Meteorological Society
Dr. ROBERT W. BURPEE	Fellow, American Meteorological Society
Dr. MARK DeMARIA	Chairman, Miami Chapter, American Meteorological Society
Mr. PETER P. DODGE	Secretary-Treasurer, Miami Chapter, American Meteorological Society
Mr. JAMES L. FRANKLIN	Working Group for Upper Air Observations, Office of the Federal Coordinator for Meteorological Services and Supporting Research: (1) Task Group for Digital Sonde Technology; (2) Task Group for Upper Air Observations Test Plan
Mr. HOWARD A. FRIEDMAN	Chairperson, Board of School and Popular Meteorological and Oceanographic Education, American Meteorological Society
	Member, Education and Manpower Commission, American Meteorological Society
	Fellow, Royal Meteorological Society
	U.S. Regional Coordinator, International Education Committee of the Royal Meteorological Society, American Meteorological Society, and the World Meteorological Organization
	Seconded Expert, Tropical Cyclone Programme Project No. 14, World Meteorological Organization
Dr. STEPHEN J. LORD	Member, American Meteorological Society Committee on Tropical Cyclones and Tropical Meteorology
Dr. FRANK D. MARKS, JR.	Chairman, American Meteorological Society Committee on Radar Meteorology
	Chairperson, Office of Aircraft Operations Instrumentation Committee
Dr. KATSUYUKI V. OOYAMA	Fellow, American Meteorological Society
Dr. MARK D. POWELL	Member, National Research Council, Natural Disaster Investigation Team

Committee Memberships (Continued)

Dr. STANLEY L. ROSENTHAL	Fellow, American Meteorological Society
	Fellow, American Association for the Advancement of Science
	Member, ERL Aircraft Allocation Advisory Panel
Dr. LLOYD J. SHAPIRO	Associate Editor, *Monthly Weather Review*
	Fellow, Cooperative Institute for Marine and Atmospheric Sciences, University of Miami
	Member, Equatorial Pacific Ocean Climate Studies (EPOCS) Council, ERL

C.2 Awards

The **1988 ERL Outstanding Scientific Paper Award** was presented to Dr. KATSUYUKI V. OOYAMA for "Scale-Controlled Objective Analysis," which appeared in *Monthly Weather Review*, Vol. 115, No. 10, pages 2479-2506.

Drs. ROBERT W. BURPEE and Leonard W. Snellman received the **1989 American Meteorological Society Special Award** for their major efforts in the successful initiation of the periodical *Weather and Forecasting*.

C.3 CIMAS Visiting Scientist

Mr. Richard E. Carbone:	National Center for Atmospheric Research, Boulder, Colorado
Research area:	Doppler radar studies in hurricanes

C.4 Visitors

Dr. Gary M. Barnes, National Center for Atmospheric Research, Boulder, Colorado
Mr. Sean Bennett, NOAA Office of Oceanic and Atmospheric Research, Rockville, Maryland
Mr. Richard E. Carbone, National Center for Atmospheric Research, Boulder, Colorado
Dr. Noel Davidson, Florida State University
Dr. Dieter Eppel, GKSS Research Center, F.R.G.
Ms. Jenni Evans, U.S. Naval Postgraduate School, Monterey, California
Dr. Steven Esbensen, Oregon State University
Capt. Michael Fitzpatrick, CARCAH, Miami, Florida
Dr. T. Theodore Fujita, University of Chicago
Dr. William Gray, Colorado State University
Dr. John Hallett, Desert Research Institute, University of Nevada
Dr. Andrew Heymsfield, National Center for Atmospheric Research, Boulder, Colorado
Dr. Yan Hong, Beijing Meteorological Center, Beijing, P.R.C.
Dr. Zhang Jijia, Beijing Meteorological Institute, Beijing, P.R.C.

Visitors (Continued)

Dr. Harmut Kapitza, University of Oklahoma; and GKSS Research Center, F.R.G.
Dr. John Lewis, NOAA/National Severe Storms Laboratory, Norman, Oklahoma
Mr. Eugene W. McCaul, Jr., University of Oklahoma
Dr. John Molinari, State University of New York at Albany
Dr. Reginald E. Newall, Massachusetts Institute of Technology,
Mr. Takashi Ohshima, Meteorological Satellite Center, Tokyo, Japan
Dr. Lynn K. Shay, U.S. Naval Postgraduate School, Monterey, California
Dr. David Soderman, European Centre for Medium Range Weather Forecasts, Reading, Berkshire, U.K.
Dr. Chung-Hsiung Sui, University of Maryland
Dr. Calvin Swift, University of Massachusetts
Dr. Roger Wakimoto, University of California at Los Angeles
Dr. Edward J. Walsh, NASA, Greenbelt, Maryland
Dr. Edward J. Zipser, National Center for Atmospheric Research, Boulder, Colorado

C.5 HRD Staff on September 30, 1988

Stanley L. Rosenthal, Deputy Director, AOML
Juanita A. Simpkins, Secretary

James W. Trout, Assistant Program Manager
Supervisory Meteorologist

Arnhols, Constance A.	Writer-Editor
Barry, William P.	Computer Programmer
Berkeley, Joyce O.	Meteorological Technician
Black, Michael L.	Meteorologist
Black, Peter G.	Meteorologist
Black, Robert A.	Meteorologist
Burpee, Robert W.	Supervisory Meteorologist
DeMaria, Mark	Meteorologist
Dodge, Peter P.	Meteorologist
Dorst, Neal M.	Meteorologist
Ewbank, Paul C.	Computer Assistant
Franklin, James L.	Meteorologist
Friedman, Howard A.	Meteorologist
Gamache, John F.	Meteorologist
Griffin, Joseph S., Jr.	Mathematician
Griffin, Nancy F.	Computer Programmer
Jones, Robert W.	Meteorologist
Kaplan, John	Meteorologist
Kohler, Robert E.	Computer Programmer
Leighton, Paul A.	Computer Programmer
Lockett, Gloria J.	Mathematician
Lord, Jacqueline M.	Computer Programmer/Analyst
Lord, Stephen J.	Meteorologist

HRD Staff (Continued)

Marks, Frank D., Jr.	Meteorologist
Marques, Frank D.	Secretary
Morrissey, Barbara J.	Computer Operator
Ooyama, Katsuyuki V.	Meteorologist
Powell, Mark D.	Meteorologist
Putland, Gerald E.	Physical Scientist
Shapiro, Lloyd J.	Physicist
Soukup, George A.	Physicist
Wiggert, Victor	Meteorologist
Williams, Helen	Computer Operator
Willis, Paul T.	Meteorologist
Willoughby, Hugh E.	Meteorologist
Wright, Robert E.	Meteorological Technician

ACRONYMS AND ABBREVIATIONS

AMS	American Meteorological Society
AOML	Atlantic Oceanographic and Meteorological Laboratory
ATOLL	analysis of the tropical oceanic lower layer
AXBT	airborne expendable bathythermograph
AXCP	airborne expendable current profiler
BSPMOE	Board on School and Popular Meteorological and Oceanographic Education-AMS
CALM	cognitive and affective learning model
CARCAH	Chief, Aerial Reconnaissance Coordinator, All Hurricanes
CIMAS	Cooperative Institute of Marine and Atmospheric Science
CISK	conditional instability of the second kind
CLASS	Cross-Chain Loran-C Atmospheric Sounding System
CMS	Chinese Meteorological Society
CSIRO	Commonwealth Scientific and Industrial Research Organization
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium Range Weather Forecasts
EMEX	Equatorial Mesoscale Experiment
EMU	Education and Manpower Commission-AMS
EPOCS	Equatorial Pacific Ocean Climate Studies
ERL	Environmental Research Laboratories
F.R.G.	Federal Republic of Germany
GALE	Genesis of Atlantic Lows Experiment
GALE/CASP	GALE/Canadian Atlantic Storms Program
GOES	Geostationary Operational Environmental Satellite
HBL	hurricane boundary layer
HRD	Hurricane Research Division
IAMAP/ICCP	International Association of Meteorology and Atmospheric Physics/International Commission on Cloud Physics
IPV	isentropic potential vorticity
LPATS	Lightning Position and Tracking System
LRCS	League of Red Cross Societies
MIT	Massachusetts Institute of Technology
MONEX	Monsoon Experiment
NCAR	National Center for Atmospheric Research
NHC	National Hurricane Center
NMC	National Meteorological Center
NSF	National Science Foundation
NSSL	National Severe Storms Laboratory
NWS	National Weather Service

OAO	Office of Aircraft Operations
ODW	Omega dropwindsonde
PBL	planetary boundary layer
P.R.C.	People's Republic of China
PRE-STORM	Preliminary Regional Experiment - Stormscale Operational and Research Meteorology
PV	potential vorticity
QBO	quasi-biennial oscillation
QE2	Queen Elizabeth 2
QSTING	quasi-spectral time integration on nested grids
RAM	relative angular momentum
RMS	Royal Meteorological Society
SAB	Satellite Applications Branch
SAFER	spectral application of finite element representation
SFMR	stepped-frequency microwave radiometer
SLOSH	sea, lakes, and overland surges from hurricanes
SSEC	Space Science and Engineering Center
SSM/I	special sensor microwave/imager
STORM	Stormscale Operational and Research Meteorology
SUNY	State University of New York
TD	Tropical Depression
TIROS	Television and Infrared Observation Satellite
UNDRO	Office of the United Nations Disaster Relief Co-ordinator
UW	University of Washington
VAS	VISSR Atmospheric Sounder
VDUC	VAS Data Utilization Center
VISSR	Visible and Infrared Spin-Scan Radiometer
WMO	World Meteorological Organization