HURRICANE RESEARCH DIVISION

FISCAL YEAR 1989 PROGRAMS - FISCAL YEAR 1990 PROJECTIONS

Staff, Hurricane Research Division

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
January 1990

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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 WP-3D research aircraft to acquire data sets that are analyzed to obtain a better understanding of the dynamics and energetics of the hurricane. Theoretical and numerical modeling studies of the hurricane are also in progress.

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 (GFDL) in research concerned with numerical modeling of hurricanes, with the National Severe Storms Laboratory (NSSL) in the study of landfalling hurricanes, and with the National Center for Atmospheric Research (NCAR) on problems related to hurricane rainbands. Cooperative research with other NOAA groups, Federal agencies, and universities is also in progress.

Two research flights into Hurricane Dean on 5 August marked the start of the 1989 HRD Hurricane Field Program. An inner aircraft flew patterns at 12,000, 1,500, and 20,000 ft to obtain airborne Doppler radar data. This aircraft measured a minimum surface pressure of 979 mb and maximum flight-level winds of 45-50 m s^{-1} at 1,500 ft. **A**irborne e**x**pendable **b**athy**t**hermographs (AXBT's) were dropped within 150 km of the storm center. The second WP-3D flew at its maximum altitude, released Omega dropwindsondes (ODW's), and recorded airborne Doppler radar in a ring that extended 300-450 km from the storm center.

Research flights were staged from Barbados into Hurricane Gabrielle on 3 and 5 September 1989. One of the aircraft flew in the storm core and the other on the periphery at radii of 300-450 km. The inner aircraft determined that Gabrielle had maximum low-level winds of 55 m s^{-1}, a minimum sea-level pressure of 937 mb, and a radar reflectivity pattern with two concentric eyewalls. This aircraft acquired an excellent set of flight-level data and airborne Doppler radar data. These flights estimated surface wind speed with the **s**tepped-**f**requency **m**icrowave **r**adiometer (SFMR) and collected samples of trace gases that will be analyzed by atmospheric chemists at NCAR. On the afternoon and evening of 5 September, HRD scientists on the NOAA 42 obtained flight-level and ODW data to help NHC forecasters more accurately predict Gabrielle's track.

On 14 September 1989, HRD and AOC (Aircraft Operations Center) personnel deployed from Miami to Barbados to conduct research flights in Hurricane Hugo. Research flights scheduled for 15 September were aborted as a result of mechanical problems with NOAA 42. On 17 September, however, HRD successfully completed a vortex dynamics and environmental interaction experiment in the core of Hugo. The aircraft measured the kinematic and thermodynamic structure of the hurricane within 180 km of the storm center using the airborne Doppler radar, ODW's, and the flight-level data systems. The Doppler radar data were the most comprehensive set of observations recorded by HRD in a major hurricane with the new radar data system. On 18 September, HRD collected additional data in Hugo, north of Puerto Rico.

Single-aircraft synoptic-flow experiments were conducted on 19 and 20 September. The flight patterns were designed to provide data to the National Weather Service (NWS) as Hurricane Hugo approached South Carolina. ODW and flight-level data were transmitted from the aircraft to NHC and NMC for real-time utilization. The final WP-3D flight in Hugo was a reconnaissance mission that began about 6 h before the north eyewall crossed the South Carolina coast near Charleston. Airborne data were obtained that will complement digital radar data collected by the HRD land-based radar teams deployed to the NWS offices in Wilmington, North Carolina, and Charleston.

The synoptic-scale flow on the periphery of mature hurricanes, and its impact on hurricane tracks, is a major area of HRD study. For this work, the standard observational network is supplemented by ODW's dropped from the WP-3D aircraft. These data are transmitted to NHC and to the NMC in real time where the data are used, respectively, in the preparation of the official forecast and in the initialization of dynamical hurricane track prediction models.

HRD's program of experimental hurricane track forecasting employs a numerical model that utilizes an accurate and flexible spectral method, called SAFER (**s**pectral **a**pplication of **f**inite **e**lement **r**epresentation) and provides very high quality grid nesting. Studies to test SAFER in the context of a barotropic hurricane track prediction model (code name VICBAR) are under way. VICBAR has been initialized with vertically averaged real horizontal winds and geopotential heights that are processed and analyzed using a nested spline analysis code developed at HRD. The latter assimilates data from a wide variety of platforms, including airborne Doppler radar, ODW's, NOAA WP-3D aircraft, Air Force reconnaissance aircraft, rawinsondes, and satellites.

VICBAR was tested in a research mode for cases in which ODW data were available. These cases included Hurricanes Debby (1982), Josephine (1984), Gloria (1985), Emily (1987), Floyd (1987), and Florence (1988). Results showed that the ODW data reduced the track forecast errors by 21%, 13%, and 12% at 12, 24 and 36 hours, respectively, and that the VICBAR model had considerable forecast skill relative to climatology and persistence for these cases.

A version of VICBAR that runs in real time was tested on most of the named Atlantic storms in 1989. Statistical analysis of the results is in progress. The initial data include a background field from the NMC analysis, rawinsondes, satellite winds, TIROS (Television and Infrared Operation Satellite) heights, and aircraft observations (NOAA and/or Air Force). The real-time results from 1989 were made available to NHC forecasters before forecast deadlines and official NWS guidance packages for Hurricanes Gabrielle and Hugo specifically mention NHC's use of VICBAR model results.

PERSONNEL

Composition of Full-Time Staff - FY-89

Degree	HRD Personnel
Ph.D.	12
M.S.	10
B.S.	9
B.A.	1
Paraprofessional	6

UNIVERSITY RELATIONS

Cooperative Research[1]

Organization	Research/Cooperative Investigator
Desert Research Institute, University of Nevada	Further Analysis of the Ice Phase in the Hurricane - Dr. John Hallett
National Center for Atmospheric Research	Hurricane Rainbands: Meso- and Convective-Scale Structure - Dr. Gary M. Barnes - Dr. Margaret A. LeMone
Science Applications International Corporation	Revisions to the NHC83 Model - Mr. Charles J. Neumann
State University of New York at Albany	Synoptic-Scale Influences on Hurricane Intensity - Dr. John Molinari
State University of New York at Albany	Intensity Changes in Hurricane Allen - Dr. John Molinari
University of Massachusetts	Microwave Remote-Sensing Measurements of Ocean Surface Winds in Hurricanes - Dr. Calvin T. Swift
University of Washington	Analysis of AOML/HRD WP-3D Doppler Radar Data - Dr. Robert A. Houze, Jr.

University-Associated Speakers at HRD

1989

March 22	University of Oklahoma Dr. Eugene W. McCaul, Jr.: "Dynamics of Simulated Convective Storms in Hurricane Environments"
April 10	University of Nevada Dr. John Hallett: "Evaporation and Melting of Ice Particles in the Atmosphere"
May 11	McGill University Dr. Geoffrey Austin: "The Statistical Properties of Florida Rainfall and Their Impact on Measurement Accuracy"
May 22	State University of New York at Albany Dr. Lance F. Bosart: "Environmental Factors in the Nondevelopment of a Tropical Disturbance and the Development of Hurricane Diana (1984)"

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

June 7	Massachusetts Institute of Technology Dr. Fred Sanders: "An Overview of the ERICA Project"
June 7	Colorado State University Dr. William M. Gray: "Long-Term Variations of the Tropical West Pacific Zonal Winds and Their Association With East Pacific Sea-Surface Temperature Variations"
June 9	Colorado State University Dr. William M. Gray: "Tropical Storm Genesis"
August 28	State University of New York at Albany Dr. John Molinari: "Intensity Changes in Hurricane Allen"

Adjunct Faculty Members (1989–1990)

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

Ph.D. Committee Memberships

Committee Member: Dr. Lloyd J. Shapiro

Degree Candidates: Mr. Lixion Avila
Ms. Peng Ge

Affiliation: Department of Meteorology and Physical Oceanography/Rosenstiel School of Marine and Atmospheric Science/University of Miami

FY-89 PROGRAMS - FY-90 PROJECTIONS

LABORATORY RESEARCH

1. Observational Hurricane Studies

1.1 The Synoptic-Scale Environmental Flow Around Mature Hurricanes

Goal

The synoptic-scale environmental flow experiments are designed to investigate the steering currents on the periphery of mature hurricanes. ODW's are dropped from the NOAA WP-3D aircraft to obtain the data required for these studies. The ODW's measure temperature, relative humidity, and pressure. They receive Omega navigational signals from eight transmitters that 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-89)

The ODW and flight-level data are transmitted from the aircraft to NHC and NMC in real time. The observations are used subjectively at NHC in the preparation of the official forecasts and at NMC in the initialization of dynamical hurricane track prediction models.

Two successful experiments were conducted on 19 and 21 September 1989 for Hurricane Hugo. ODW data from the environment and inner core of Hugo were gathered and transmitted to NHC and NMC as the hurricane was 24–48 h from landfall at Charleston, South Carolina. The ODW data were made available to the forecasters at NHC in real time.

An experiment for Hurricane Gabrielle on 5–6 September 1989 was terminated early because of mechanical problems on one of the two NOAA WP-3D aircraft. However, the second aircraft was able to gather and transmit data from the environment of Gabrielle ahead of the hurricane path. The ODW data played a significant role in the official NHC forecast of Gabrielle's track that was issued after the experiment.

HRD scientists use the ODW data to gain a better understanding of the interactions between the environment and the hurricane vortex. Diagnostic studies of these interactions are in progress and are described later in this report. Comparisons of VAS [VISSR (Visible and Infrared Spin-Scan Radiometer) Atmospheric Sounder] data with ODW observations are also in progress.

During FY-89, postprocessing of ODW data was completed for a VAS evaluation experiment, a synoptic-flow experiment in Hurricane Florence (1988), an energetics experiment in Hurricane Gilbert (1988), and reconnaissance flights in Hurricane Gilbert. ODW data were also processed for the Coordinated Eastern Arctic Experiment (CEAREX). A total of 155 ODW's was processed. NMC is evaluating the impact of ODW data on the NMC operational analyses and is developing a data base for the ODW cases. The data base will include all of the appropriate operational analyses and forecasts.

Plans (FY-90)

ODW data from 1989 synoptic-flow experiments will be processed and distributed to interested researchers. Plans to conduct several synoptic-flow experiments during the 1990 hurricane field program are being developed.

In cooperative studies with NHC and NMC, we will continue to examine the impact of the ODW data on the NMC operational analyses and the NMC hurricane track models.

HRD will implement software that codes ODW wind and thermodynamic observations at mandatory and significant levels. This software will be run on an aircraft workstation, which is to be installed on one of the WP-3D's in 1990. The modified software will enable HRD to transmit significant-level ODW observations from the aircraft to NHC and NMC. Researchers at NMC feel that the significant-level ODW observations will improve their ability to make use of the ODW data.

1.2 Mesoscale Precipitation Features in Mature Hurricanes

Goal

The purpose of this work is the use of airborne radar to identify the mesoscale convective features in mature hurricanes and to describe their basic organization and structure. Studies of the differences in wind, reflectivity, and vertical velocity fields between the convective precipitation regions in the eyewall and nonconvective precipitation regions surrounding the eyewall are in progress.

Accomplishments (FY-89)

Manuscripts that describe the eyewall water budget study in Hurricane Norbert on 24 and 25 September 1984 are near completion. One paper concentrates on the kinematic structure of the eyewall, with emphasis on the derivation and description of the Doppler-derived wind field and on the changes in wind structure with altitude. Another paper focuses on microphysics observations made at one flight level surrounding the storm and compares them with the radar reflectivity and wind fields.

Radar reflectivity and airborne Doppler wind have been used to construct trajectories of air parcels and precipitation particles through the storm. The trajectories show that 90% of the air in Hurricane Norbert's inner core was spinning around the core with little vertical motion.

A third paper describes techniques used to derive Hurricane Norbert's water budget. A major effort went into the implementation of algorithms to retrieve thermodynamic variables from the Doppler wind analysis. The basic goal of this effort was to deduce the fractional amounts of water in the vapor, liquid (both cloud and rain) and solid (ice) states in the analysis domain. The ice and rain amounts were determined from the radar reflectivity data; however, the cloud and vapor amounts were deduced using the thermodynamic data and microphysical retrieval.

Analysis of airborne Doppler observations from the Hurricane Emily water budget experiment on 22 September 1987 was also completed. In this case, the storm was deepening at ~ 2 mb h^{-1}. This rate compares well with that of Hurricane Norbert, which was filling at about the same rate.

Attempts to use the airborne Doppler data to supplement the ODW data in the core of Hurricane Gloria (1985) were extremely promising. The inner core wind structure matched the ODW data at the edges of the Doppler domain and the sharp wind shear region along the eyewall was clearly defined.

Work to develop real-time analysis of airborne Doppler radar observations on hurricane research flights was begun in collaboration with NCAR.

A review paper on meteorological radar observations of tropical weather systems, which was presented at the *Battan Memorial and 40th Anniversary AMS Conference on Radar Meteorology* in November 1987, has been included in the conference monograph.

Plans (FY-90)

The primary emphasis in FY-90 will be on the completion of the Hurricane Norbert papers. Work will start on a paper that compares the eyewall water budget analyses of Hurricanes Emily and Norbert.

Work will continue on the incorporation of airborne Doppler data into the analysis of the synoptic environment of Hurricanes Florence (1988), Gloria, and Emily.

1.3 Convective Rainbands in Hurricanes

Goal

The goal of this research is an understanding of the role of hurricane rainbands in the determination of hurricane structure and intensity. The thermodynamic modification of boundary-layer air flowing toward the storm center is often modified by downdrafts within the rainbands. These downdrafts can produce changes in storm intensity.

Accomplishments (FY-89)

Analyses of the kinematic and thermodynamic structure of the hurricane boundary layer in Hurricane Earl (1986) were combined with those from a limited experiment in Hurricane Josephine (1984) and then compared with results of recent experiments conducted in rainbands closer to the eyewall in Hurricanes Floyd (1987) and Irene (1981). Results indicate that outer rainbands have many common features in the precipitation, wind, temperature, and humidity fields and can exert a strong influence on the hurricane boundary-layer structure. These results were presented at the AMS *24th Conference on Radar Meteorology* in Tallahassee in March 1989 and at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

A combined rainband/boundary-layer experiment was flown on the southeast side of Hurricane Gilbert (1988) on 12 September. A secession of convectively active rainbands formed in a region ~100 km to the southeast of the storm center; several of these rainbands were documented.

In cooperation with NCAR scientists, we have completed analyses of the flight-level data for two of six flights into Tropical Storm Isabel (8-10 October 1985). Preliminary results (presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology*) indicate that a second storm center developed beneath a "supercell" convective complex that was 60 km north of the original center and became the dominant center. The circulation associated with this new center was insufficient to maintain convection long enough for the tropical storm to develop into a hurricane, however.

In a cooperative project, NCAR scientists completed a manuscript on Hurricane Raymond (1983) in which Doppler wind fields were composited with respect to a radar echo.

Plans (FY-90)

Studies of a GALE (Genesis of Atlantic Lows Experiment) rainband and rainbands in Hurricane Gilbert and Tropical Storm Isabel (1985) will be continued cooperatively with NCAR scientists.

1.4 Vortex Motion and Dynamics

Goals

The goals of this research are the improvement of our understanding of hurricane dynamics and the forecasting of hurricane motion through analysis of observations made by research aircraft and through formulation of relatively simple quasi-analytical models.

Accomplishments (FY-89)

Research flight operations in Hurricanes Florence, Gilbert, and Joan of 1988 provided further confirmation of the convective ring model of tropical cyclone intensification. In the Hurricane Gilbert case, after a day of rapid intensification, a spectacular outer concentric eyewall formed, and the preexistent inner eye wall weakened before the storm made landfall on the Yucatan Peninsula.

A by-product of the Hurricane Gilbert flight was the establishment of a new record minimum surface pressure of 888 mb for an Atlantic hurricane. Improved postseason processing software allowed completion of track construction and preliminary analysis for the 1988 data before the end of calendar year 1988. HRD's archive of vortex evolution data now contains 977 radial profiles observed since 1977 in 19 hurricanes and/or tropical storms.

Studies of vortex evolution and wind balance based upon pre-1988 observations were completed.

The 1988 season provided a definitive test for real-time processing of aircraft observations in hurricanes. Although this capability has been available since 1986, all of the earlier operational testing was done on minimal hurricanes. In 1988, however, the system was able to analyze the small, intense inner eye of Hurricane Gilbert and detect the formation of the outer eyewall.

Software development began for evaluation of objectively determined storm motions in track forecast initiation.

HRD has provided a terminal that allows the NHC hurricane specialists to do real-time integration and processing of data gathered by the NOAA WP-3D aircraft.

A continuing study of linear motion of a shallow-water barotropic vortex showed that only a single, neutral, normal mode at zero frequency exists when the circulation is cyclonic throughout the vortex. A conjugate pair of barotropically unstable growing and damped modes exists in addition to the neutral mode when an annulus of anticylonic circulation at the periphery makes the total relative angular momentum (RAM) of the vortex small. The unstable mode has a frequency equivalent to the most anticyclonic orbital frequency of the mean circulation, and its growth rate is slow, ~75 days. The forced solution on a beta plane leads to meridional propagation of the vortex so that conservation of absolute angular momentum acts to adjust the RAM toward zero. Wave momentum fluxes associated with the motion act to expand the vortex, although in this linear model, they do not change its total RAM appreciably. Conceptual formulation of a nonlinear, prognostic version of this model is complete, but code development has not begun.

Plans (FY-90)

Research will focus primarily on empirical studies of cyclone motion. We plan to complete evaluation of the role of objectively determined initial motions in track forecasting and to examine the archive of aircraft observations for relationships between asymmetric features of the wind or mass fields and vortex motion.

Development of improved real-time and postseason software will include alternative track determination algorithms in addition to better displays, more automation, and improved communications. With the foregoing improvements, the real-time software should approach its final form by the end of the 1990 hurricane season. Testing and evaluation of the real-time software will be the main goal of flight operations. We expect to start coding the nonlinear vortex motion model and to have some preliminary results this year.

1.5 Microphysical Studies in Hurricanes

Goal

The goal of this research is a description of the water contents, liquid and ice particle number concentrations, density spectra, particle phase partitioning, and generation and depletion rates within the dynamic framework of the hurricane. Emphasis will be on determination of the microphysical characteristics of hurricane clouds as a function of the measured vertical velocity of the air at meaningful structural locations within the storm. Equal emphasis will be given to a comparison of the microphysical characteristics and overall importance of convectively active regions of the storms with the stratiform regions.

There is increasing evidence that the stratiform regions and melting layers play an important role in hurricane energetics. Stratiform interactions with convective regions may influence the location, organization, and strength of important convective features, such as the eyewall and the active rainbands.

Accomplishments (FY-89)

A manuscript on drop size distributions in intense rainfall was published in the January 1989 *Journal of Applied Meteorology*. A paper on the melting layer in mesoscale convective complex stratiform precipitation, co-authored with an NCAR scientist, appeared in the July 1989 *Journal of the Atmospheric Sciences*. A paper on hurricane microphysical trajectories was presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

An analysis of the advecting spiral descent in a stratiform region of Hurricane Emily (1987) has been started. A note, "Radar Reflectivity - Ice Water Content Relationships for Use Above the Melting Level in Hurricanes," was submitted to the *Journal of Applied Meteorology*. This work describes the radar reflectivity - ice water content (Z–M) relationships in Hurricanes Norbert (1984) and Irene (1981) and shows that the slope of the Z–M relation was almost equal in stratiform and convective areas, but the intercept was greater for the convective areas. This difference reflected the greater ice particle density in the convective areas.

A study of Hurricane Emily's vertical wind, radar reflectivity, and eye thermodynamic structure is near completion. The strongest updrafts were found in the left- and right-front quadrants. The highest mean speed of the strongest 10% of the updrafts was 9.8 m s^{-1} in the left-front quadrant. The peak 1-s vertical velocity was 23.9 m s^{-1} in the right-front quadrant. Similarly, the greatest mean speed of the upper 10% level downdrafts was −8.0 m s^{-1} in the left-rear quadrant, and the strongest peak downdraft was −18.8 m s^{-1} in the same quadrant.

Preliminary analysis of the microphysical data from Hurricane Emily on 22 September 1987 was completed. Most of the eyewall data were obtained at 0°C. The peak cloud liquid water observed with the Johnson-Williams device was ~2.3 g m^{-3}. As has been noted in other hurricanes, downdrafts usually contained ice crystals in concentrations $> 100\ \ell^{-1}$, and the only identifiable ice crystal types were columns and graupel.

Plans (FY- 90)

Work is continuing on the adaptation of NCAR's microphysical trajectory model to the hurricane situation. Numerous model runs have been made on Hurricane Norbert.

The Desert Research Institute induction ring will be used to obtain measurements of the charge carried by ice particles in hurricane convection. The field mills will provide data on the vertical component of the storm electric field. All software necessary to collect and analyze the electric field and particle charge data will be developed. The electrical data will be fully integrated with the normal microphysical and radar data sets.

A cooperative study with NCAR concerning the trajectories of ice particles from the eyewall and convective features of the rainbands will be continued during this period. We plan to apply numerical models of hydrometeor growth in an attempt to assess how much of the ice mass in hurricane stratiform precipitation areas is added in situ by particle growth, and how much is due to transport into these regions from more convective regions.

Analysis of the data from an isolated oceanic cumuli experiment (that includes microphysical data, formvar data, radar, vertical incidence Doppler, and airborne Doppler wind data) will be started.

Analysis of stratiform regions in hurricanes, particularly those from Hurricane Newton (1986), will be continued. A study to relate eyewall development and hurricane intensity changes to the locations, patterns, and stage of development of stratiform precipitation areas in a representative sampling of storms will be continued.

1.6 Convective- and Mesoscale Structure of Landfalling Hurricanes

Goal

The goal of this project is the analysis of digital data that are recorded by the NOAA hurricane research aircraft and/or NWS WSR-57 radars during and near the time of landfall of hurricanes. The emphasis of the research is on the description of important changes in the convective-scale and mesoscale patterns of precipitation that are caused by the storm's approach to land.

Accomplishments (FY-89)

A manuscript on the temporal and spatial variations of rainfall near the centers of Hurricanes Alicia (1983) and Elena (1985) was published in the September 1989 *Monthly Weather Review*.

A correction for radar reflectivity, based upon the variation of average returned power with range in four hurricanes, was developed. The results were described at the AMS *24th Conference on Radar Meteorology* in Tallahassee in March 1989.

The NOAA WP-3D aircraft collected ~92 h of radar data as Hurricane Elena intensified from a weak tropical storm to a mature hurricane with a minimum surface pressure of 951 mb. Hurricane Elena's eye tracked toward the northwest for 2 days, recurved toward the northeast for 1 day, stalled for nearly 1 day, and then headed northwestward. Descriptions of variations in this storm of the precipitation patterns relative to changes in storm motion and intensity are being prepared. Preliminary results were presented at the AMS *24th Conference on Radar Meteorology*.

A project to analyze hurricane vertical motions measured by airborne Doppler radar was started. Airborne Doppler data were obtained in Hurricane Elena on six reconnaissance flights at 1,500 m and vertical velocities were obtained at altitudes ranging from 0.3 to 15 km. Reliable Doppler data are available from 59 radial penetrations of the eyewall that spanned the transition of Hurricane Elena from a tropical storm with a poorly defined eyewall to a mature hurricane with a closed eyewall. Preliminary results were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

The concentric eyewalls observed in Hurricane Gilbert (1988) have been documented by airborne radar data.

HRD's land-based radar teams recorded digital data from NWS WSR-57's during the landfalls of Hurricanes Florence and Gilbert of 1988. Florence was a minimal hurricane as it approached the Louisiana coast. HRD teams monitored the storm from Slidell, Louisiana, and Mobile, Alabama. During the landfall of Hurricane Gilbert, two teams went to the NWS WSR-57's at Brownsville and Corpus Christi, Texas. The eye made landfall in Mexico ~200 km south of Brownsville.

HRD deployed two teams, on 21 September 1989, to record radar data at Charleston, South Carolina, and Wilmington, North Carolina, during the landfall of Hurricane Hugo. The cyclone was a category-four storm on the Saffir/Simpson scale as it made landfall near Charleston. The center of Hugo passed directly over the NWS radar site at Charleston and the eye could be tracked by the Wilmington radar even when Hugo was > 100 mi inland.

In cooperation with NASA/Goddard scientists in the Tropical Rainfall Measuring Mission (TRMM), one of the HRD radar recorders was installed at the NWS WSR-57 at Daytona Beach, Florida, from May to July 1989.

Plans (FY-90)

Analyses of radar reflectivity data from Hurricane Elena and airborne Doppler radar data from Hurricane Gilbert will be completed. A paper that describes the kinematic and radar reflectivity structure of Hurricane Gilbert's eyewall region in comparison with the eyewall structures of Hurricanes Norbert (1984), Gloria (1985), and Alicia will be started.

Work will continue on the processing of vertical motions measured by airborne Doppler radar in the core of hurricanes. The goal is the processing of ~150 cross sections. Up- and downdrafts will be composited in the total sample, and separately, for the eyewall, rainbands, and stratiform areas.

The analyses of the concentric eyewall cycle in Hurricane Gilbert will be completed and a note describing the results will be submitted for publication.

1.7 Hurricane Boundary-Layer and Air-Sea Interaction Studies

1.7a Boundary-Layer Studies

Goals

To study the hurricane boundary layer, relationships between flight-level winds measured by reconnaissance aircraft at various altitudes and the winds at the underlying surface will be developed.

Surface data collected by ships of opportunity, buoys, platforms, coastal automated stations, hourly and synoptic reporting stations, and reconnaissance aircraft observations adjusted to the surface will be used to develop an objective analysis system for operational use by NHC.

The transition of the hurricane boundary layer from its open ocean state to a subsequent condition of decay after landfall will be documented to determine the kinematic and thermodynamic changes that occur and how they relate to decreases in storm intensity and strength.

Accomplishments (FY-89)

A data base of aircraft-buoy comparisons was expanded to include all comparisons within $\pm$ 20 km and $\pm$ 4 h through the 1988 hurricane season. We created an additional data base that contains comparisons of maximum visually estimated surface winds and maximum measured flight-level winds based upon vortex message reports collected from 1975 through the present. Results thus far indicate that the relationship between aircraft and buoy-measured winds is strongly dependent upon stability. A paper summarizing these results was presented at the *6th U.S. National Conference on Wind Engineering* in Houston, Texas, in March 1989 and at the *43rd Annual Interdepartmental Hurricane Conference* held at Homestead Air Force Base in January 1989.

Experimentation was started on the application of the HRD objective analysis system to a set of surface observations and ASDL (aircraft-satellite data link) winds that were archived from Hurricane Gilbert (1988) during a 14-h period centered on 0000 UTC 16 September in the south central Gulf of Mexico. Analyses were conducted on the basin scale (20° x 20°) and on the vortex scale (4° x 4°).

HRD scientists met with NSSL mobile laboratory to collect Cross-Chain Loran Atmospheric Sounding System (CLASS) observations in Kingsville, Texas, while Hurricane Gilbert made landfall in Mexico 200 miles to the south. Several outer rainbands were documented (some of which spawned tornadoes nearby) and excellent thermodynamic data were collected.

Plans (FY-90)

A manuscript that describes the estimation of oceanic surface winds in hurricanes from relationships between reconnaissance aircraft and oceanic platforms will be drafted. This paper will describe relationships between NOAA aircraft and buoy observations that have been gathered over the past 10 years. Comparisons of visual sea-state maximum wind estimates with maximum flight-level measurements, dependence of the surface-to-flight-level wind ratio upon flow fetch and convection, and relationship of the vertical profile of the horizontal wind to these parameters will be the subjects of future papers.

We will complete an objective analysis of one storm and determine the usefulness of the analysis to NHC. In combination with this effort, the current boundary-layer model that adjusts wind speeds to the surface will be updated and a surface wind direction algorithm will be designed and implemented.

NSSL and HRD, jointly, will attempt to gather upper air data by use of the NSSL mobile CLASS system, if an appropriate hurricane landfall occurs in 1990. The addition of a Loran station in the southwest U.S. should allow improved documentation of the vertical wind, temperature, and humidity profiles if a landfalling hurricane strikes the Gulf Coast.

1.7b Air-Sea Interaction Studies

Goal

The goal of this research is the study of the structure and dynamics of the atmospheric and oceanic boundary layers in tropical cyclones.

Accomplishments (FY-89)

A joint NOAA/Navy air-sea interaction experiment was conducted in the Gulf of Mexico from NOAA hurricane research aircraft before, during, and after the passage of Hurricane Gilbert (1988). The objective of the experiment was to assess the role of turbulent mixing and horizontal advection processes on near-inertial time scales in the ocean response to hurricanes. The experiment involved five WP-3D flights: one before the storm, two within the storm, and two after the storm made landfall. Measurements of ocean currents and temperature profiles from the surface to 1,500 m were made with **a**irborne **e**xpendable **c**urrent **p**rofilers (AXCP'S). In other locations, the temperature profile to 300 m was measured with AXBT'S. From 14 to 19 September, 92 AXCP'S and 60 AXBT'S were deployed. In addition, more than 25 NOAA-10 high-resolution infrared satellite images over the Gulf of Mexico were acquired from 13 to 20 September.

Little change in **s**ea-**s**urface **t**emperature (SST) was observed over the western Caribbean during Hurricane Gilbert's explosive deepening to a record 888 mb on 13 and 14 September. However, a dramatic decrease in SST accompanied the storm's traverse of the Gulf of Mexico on 15 and 16 September. A gradual basin-wide decrease in SST from 30°C to 28°C preceded the arrival of the storm. A further SST decrease to 25°C abruptly followed in the storm's wake over a 100- to 200-km-wide area to the right of the storm, except for an area in the central Gulf dominated by a warm anticyclonic eddy. This pattern was graphically illustrated by enhanced, high-resolution, water-vapor-corrected NOAA-10 satellite imagery. The small SST decreases in the Caribbean Sea and Gulf eddy water are attributed to the initial **m**ixed-**l**ayer **d**epths (MLD's) > 70 m. The large SST decreases across the undisturbed Gulf are attributed to the initial MLD's of < 30 m.

Strong mixed-layer currents associated with gravity-inertia waves generated by the storm were measured to the right of the storm track 1.5 and 3 days after storm passage. Current magnitudes were $\sim 1.5 \text{ m s}^{-1}$. A reversal in current directions occurred immediately below the mixed layer with very strong vertical shears in the upper thermocline. Thus, a large area of the Gulf was set in motion by Hurricane Gilbert and this motion persisted for 7 to 10 days after storm passage.

A paper on the buoy observations made in Hurricane Josephine (1984) appeared in the December 1988 *Journal of Atmospheric and Oceanic Technology*. Another paper, co-authored with U.S. Naval Postgraduate School scientists on the vertical ocean structure derived from the Hurricane Norbert (1984), Josephine (1984), and Gloria (1985) AXCP data, was published in the May 1989 *Journal of Physical Oceanography*. An overview of the AXBT and AXCP observations in Hurricane Gilbert was presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in May 1989.

In collaboration with NHC, an evaluation was begun of the **s**pecial **s**ensor **m**icrowave/imager (SSM/I) aboard a DMSP (**D**efense **M**eteorological **S**atellite **P**rogram) satellite to determine its usefulness in measuring surface winds in and around hurricanes. Special flight patterns were flown with the two WP-3D aircraft in Hurricane Gilbert coincident with SSM/I overpasses. Comparisons of the aircraft flight-level winds and SFMR surface winds with the SSM/I satellite winds were made. Comparisons of the airborne-radar-derived rain rates were made with the 85-GHz channel data. Virtually no useful SSM/I wind data were found within the inner core of the storm. Good agreement was found with precipitation features, because SSM/I resolved rainband-scale features quite well. Preliminary results were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* and *4th Conference on Satellite Meteorology and Oceanography*.

Plans (FY-90)

We will use an improved version of the SFMR algorithm on the aircraft during the 1989 hurricane season and, in 1990, will begin real-time transmission of surface winds to NHC. Analysis of the 1984-88 SFMR data will continue. Work on the collaborative satellite-aircraft surface wind evaluation program with NHC will also continue. Data gathered during the 1988 program will be analyzed in detail.

An in-depth analysis of the Hurricane Gilbert ocean response experiment will continue. About 10 NOAA polar orbiting satellite images that are archived at the University of Miami and NORDA (Naval Oceanographic Research and Development Authority) will be analyzed to complement the difficult analysis of AXCP data in the vicinity of eddy features. Data from the 1988 ocean response and atmospheric boundary-layer experiment will be analyzed in collaboration with scientists at the U.S. Naval Postgraduate School. The ocean response experiment will concentrate on measuring the details of the storm-induced internal wave response.

1.8 Tropical Cyclone Supercell Structure

Goal

The goal of this project is an understanding of the thermal, dynamical, and microphysical structure of large supercells within tropical cyclone circulations.

Accomplishments (FY-89)

Large convective bursts, which last 12 to 24 h and consist of several shorter period convective pulses, sometimes occur near tropical cyclone wind maximum. These events disrupt trends in storm deepening for as long as 1 to 2 days. Following this disruption, rapid deepening sometimes occurs.

We have continued our analysis of airborne Doppler radar wind data and radar reflectivity data for a Hurricane Norbert supercell on 22 September 1984. Preliminary results show that the wind and reflectivity features associated with the core of the supercell in the southwest quadrant have an outward and upward tilt with height and that the storm circulation center has a tilt toward the northwest with increasing height. The center at 9-km altitude was displaced 15 km west-northwest of the center at 3-km altitude. Satellite high-cloud motions from GOES (Geostationary Operational Environmental Satellite) data showed the existence of an upper level jet impinging on the storm from the southeast that appeared to play a role in the observed tilt of the vortex axis as well in the subsequent change in storm motion from northeastward to northwestward.

The Hurricane Norbert data were compared with those for another supercell storm, Hurricane Gladys (1975). High-cloud motions for Hurricane Gladys also revealed an easterly jet impinging on the storm at the time of supercell occurrence. The interaction of the easterly jet with the storm circulation seemed to produce a vertical motion couplet (down on the east side of the storm and up on the west side) that generated anomalously warm, dry air at low levels. This dry air was then advected from the east to the west side of the storm and resulted in a Midwest severe-weather-type sounding in the presence of forced ascent. Intense supercell convection was the consequence.

A large supercell was observed in Diana (1984) just before rapid intensification. In this case, frequent lightning discharges were observed by the Lightning Position and Tracking System (LPATS) Florida lightning network that were concurrent with aircraft data. The radar reflectivity structure and location on the south side of the circulation center were similar to the supercells of Hurricanes Norbert and Gladys.

Preliminary analysis of the LPATS data indicates that the majority of lightning strokes from Hurricane Diana during the daytime came from three 20-minute-long bursts, which originated from the supercell region, at ~90-minute intervals.

Plans (FY-90)

We will continue the analyses for Hurricanes Norbert, Diana, and Gladys supercells. Lightning data for a fourth supercell case, Tropical Storm Isabel (1985), have been obtained and will be combined with data that are being analyzed at NCAR. An effort will be made to construct a qualitative model of the thermodynamic, kinematic, and microphysical structure of a supercell. Analysis of the satellite images and surrounding environmental flow data will be initiated for these cases.

2. Quasi-Spectral Hurricane Model

Goal

The goal of this research is the prediction, from physical principles, of the motion, intensity and structure of hurricanes. To attain this goal, the complex problem of interaction between different dynamic regimes and physical processes in the three-dimensional moist atmosphere must be addressed. To facilitate the division and synthesis of individual phases of research, a general-purpose base model (code name: QVADIS) has been developed that utilizes an accurate and flexible numerical method, called SAFER. The current focus of this work is on the formulation of moist physics for a three-dimensional hurricane model.

Accomplishments (FY-89)

The CYBER-205 version of the two-dimensional QVADIS model on movable, multinested horizontal domains is being used by other HRD investigators for several research projects. These projects include an investigation of vortex dynamics on a beta plane, a study of the effect of initial asymmetry on hurricane motion, and real-time barotropic predictions of hurricane motion with real observational data.

In the history of numerical weather prediction, moisture and moist thermodynamic processes have often been treated as secondary additions to the dry atmosphere. However, a unified formulation of moist thermodynamics is necessary in a hurricane model that must cover all scales.

During the past year, a theoretical study of this problem was initiated. It was proposed that prediction should be made strictly in terms of conservation laws. Thus, mass, momentum, and entropy are prognostic variables. On the other hand, neither pressure nor temperature are conservative properties. Thus, these must be diagnostic variables of the model. We believe that the proposed formulation of thermodynamics in the "primitive" form would simplify a hurricane model, both conceptually and numerically.

The atmosphere is highly stratified, and the representation of the vertical structure is important. After a careful examination of commonly used methods, it was decided to adopt the SAFER method in the vertical. Although the advantage of the SAFER method has been clearly demonstrated by the success of our two-dimensional QVADIS model, its application in the vertical requires new boundary conditions.

In design and construction of the basic two-dimensional QVADIS model, we have meticulously avoided ad-hoc assumptions and shortcuts and always sought for, and followed, theoretical guidance to make major decisions. The price of this policy was the time spent in completion of these theoretical studies, but it is now paying off in terms of ease and dependability of applications. It is a great challenge to follow the same policy in the planned three-dimensional model with full physics. However, the present phase of building a foundation by components is near completion, and tests of the assembly of components will begin before the end of this fiscal year.

A theoretical experiment has been made to combine the saturation vapor pressure over water with the same over ice, as a simplified means of dealing with the three phases of water in clouds, within the context of reversible thermodynamics. The intended goal is synthesis of a hypothetical water substance whose thermodynamical behavior gradually shifts from liquid water to ice, and vice versa, in a predetermined temperature zone. The hypothesis will not substitute for irreversible microphysical processes governing clouds and precipitation, but it should be an improvement over the commonly adopted no-ice assumption in many existing models.

Plans (FY-90)

Preliminary tests of modeled physical processes with a two-dimensional model representing the stratified atmosphere in a vertical plane will be made. In addition to the new formulation of reversible moist processes, the modeled physics must include irreversible processes, such as eddy fluxes and microphysical processes of precipitation. To the best of our knowledge, they are describable only by empirical formulas and are subject to various degrees of approximation. The question is the adequacy of such assumptions in the total context of a model. It is prudent to test them in a simpler two-dimensional model before going to three dimensions.

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

Goal

The objective of this study is a test of the spectral nesting technique SAFER (see above) in the context of the simplest system of equations that can be used for hurricane track prediction. The model is initialized with real data and these tests will determine its applicability to operational forecasting of hurricane tracks as well as provide insight needed for application of the method to fully three-dimensional simulations.

Accomplishments (FY-89)

The SAFER technique was applied to a barotropic hurricane track prediction model (nicknamed VICBAR) that solves the shallow-water equations on a Mercator projection. The model is initialized with real data. Vertically averaged horizontal winds and geopotential heights are analyzed using the nested spline analysis code developed at HRD. The analyzed fields are interpolated to the model grid and then the height field is calculated from the wind field using the nonlinear balance equation on all of the interior meshes. The observed vertically averaged heights are used on the outer mesh, which provides boundary conditions for the balance equation.

VICBAR was tested for cases for which ODW observations were available. These cases included Tropical Cyclones Debby (1982), Josephine (1984), Gloria (1985), Emily (1987), Floyd (1987) and Florence (1988). Forecasts were made with and without the ODW's in the initial analyses. Results showed that the ODW data reduce the track forecast errors by 21%, 13% and 12% at 12, 24 and 36 h respectively. These results also showed that the VICBAR model has considerable forecast skill relative to the CLIPER (climatology/persistence) model for the 11 ODW forecast cases. Results from this study were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

A version of the VICBAR model was developed that can be run in near real time. The data include a background field from the NMC analysis, rawinsondes, satellite winds, TIROS heights, and aircraft observations (NOAA and/or Air Force). For this case, winds and heights are analyzed at four levels (850, 700, 500 and 200 mb). These are then vertically averaged from 850 to a top pressure between 400 and 200 mb, where the top is chosen so that the average environmental wind surrounding the storm is as close as possible to the current storm motion estimate. A special "scan" type analysis has been developed that is formulated in storm-relative cylindrical coordinates. This system is used to analyze aircraft and other observations within ~400 km of the storm center. The scan analysis eliminates the need for a bogus vortex in the VICBAR model, provided that aircraft observations are available. This system has been tested for Tropical Storms Allison and Barry and Hurricanes Chantel, Dean, Erin, and Hugo, all of which occurred in 1989. The track forecasts for these storms were made available to the forecasters at NHC. Two of the forecasts for Hurricane Hugo used an analysis that included the ODW observations. Preliminary results indicate that the VICBAR model has significant skill relative to the climatology and persistence forecasts (from the CLIPER model).

Plans (FY-90)

The near real-time analysis and prediction will continue through the 1989 season. Modifications to the analysis and prediction system will be made throughout the season to try to improve the timeliness of the forecasts. When the season is over, the skill of the VICBAR forecasts will be determined by comparison with the best-track and other operational track prediction models. Also, the forecasts will be repeated using a bogus vortex and compared with the forecasts where the storm circulation is determined from observations.

After the 1989 hurricane season, work will continue on the ODW cases. In tests during FY-89, the wind data were vertically averaged and then analyzed. This was no problem for the background field and the rawinsonde data, because these were available through most of the troposphere. However, the ODW's only extend up to ~400 mb and the flight data are at a single level. Thus, it was necessary to make assumptions about the relationship between the aircraft winds and the deep-layer mean winds. To eliminate the need for these assumptions, the forecasts for the ODW cases will be repeated using the system developed for real time, except that analyses will be done at 400 and 300 mb, in addition to 850, 700, 500 and 200 mb.

4. Initialization of Tropical Cyclone Models

Goal

The objective of this study is the investigation of methods for initializing tropical cyclone prediction models. The applicability of normal-mode initialization techniques to hurricane prediction is investigated using a three-layer axisymmetric model. A new data assimilation technique, based upon a least-squares fit of data to a model (sometimes referred to as the "adjoint method"), is studied using a simple equivalent barotropic model. Both of these methods may help to improve tropical cyclone forecasts by making better use of initial data and by eliminating unrealistic model imbalances.

Accomplishments (FY-89)

The applicability of normal-mode techniques to tropical cyclone prediction has been studied using a highly truncated axisymmetric hurricane model. Results show that the iterative procedures used to solve the initialization equations are likely to diverge under tropical cyclone conditions. These results were generalized to the full version of the axisymmetric model and to a version of the truncated model, which included nonlinear interactions. An alternate normal-mode scheme was found that does not require an iterative solution.

Some preliminary work was done to study the adjoint method. A grid-point nondivergent barotropic model on a beta plane with simple lateral boundary conditions was adapted to the VAX computer. Code was developed to obtain the boundary streamfunction from the horizontal wind in preparation for simulations with more general boundary conditions. The adjoint model appropriate to the above grid-point model was derived.

Plans (FY-90)

The study of normal-mode initialization is almost complete. Recent work on the application of normal-mode techniques to mesoscale models has raised some question about the assumptions made in applying these techniques when diabatic heating is present. This question will be addressed when the axisymmetric model is used.

In FY-90, the main emphasis of this project will be on the adjoint method. The barotropic model will be generalized to include a Mercator map projection and more general boundary conditions. Graphics routines also will be developed for the model output. Once this work has been completed, the adjoint model will be coded. The adjoint model has many similarities with the barotropic model and many of the same subroutines can be used. Once the coding has been completed, the data assimilation technique will be tested in idealized cases. Model-generated data will be used to give insight into the behavior of the scheme for the case where the data coverage can be controlled. Two types of problems will be considered. The first is related to the assimilation of aircraft data for hurricane track prediction, and the second is related to large-scale prediction of the tropical wind field.

5. Asymmetric Evolution of the Hurricane

Goal

The objective of this research is the evaluation and prediction of the evolution of the asymmetric structure 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. The research is designed to provide increased understanding of the physical processes that affect hurricane motion, as well as insight into model formulation, interpretation, and initialization procedures for real-data forecasts.

Accomplishments (FY-89)

A barotropic, primitive equation (shallow-water) model on the beta plane was used to investigate the influence of divergence, total RAM and advective nonlinearities on the evolution of a hurricane-like vortex. A preliminary study has been completed and submitted for formal publication. The multinested SAFER numerical method was employed. The undisturbed fluid depth was taken to be 1 km. Scaling of the vorticity equation indicates that divergence should have a very small effect on hurricane motion. The numerical simulations with an initially symmetric vortex in a resting environment confirm this analysis. These results differ from previous published studies on the effect of divergence. During a 120-hour simulation, a cyclonic vortex develops asymmetries that have an influence far from the initial circulation. The total RAM within a large circle centered on the vortex decreases with time and then oscillates about zero. For circles with radii less than ~1,000 km, the total RAM approaches, but does not reach, zero. An angular momentum budget indicates that the horizontal angular momentum flux tends to counteract the net Coriolis torque on the vortex. If the total RAM of the initial symmetric vortex is zero, the weak far-field asymmetries are eliminated. The motion of the vortex is not, however, related to the RAM in any simple way.

The near-vortex asymmetries reach a near-steady-state within a few days. The asymmetric absolute vorticity (AAV) is nearly uniform within ~350 km of the vortex center. A homogenization of AAV, which occurs within the closed vortex gyre, is probably due to shearing by the symmetric wind, combined with removal of energy at the smallest scales. The homogenization effectively neutralizes the planetary beta effect, as well as the vorticity associated with an environmental wind. The results of this research were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

Plans (FY-90)

A three-layer model is being developed to investigate the asymmetric structure and evolution of the hurricane vortex, and its interaction with the large-scale environment, in a more realistic physical context than the barotropic model described above. The three-layer model is the simplest formulation that can incorporate the effect of boundary-layer dissipation, convective heating, momentum transports, and vertical variations in the large-scale environment. Experiments will be designed to evaluate the effect of the internal and external sources of heat and momentum, and vertical wind shear on the results from the barotropic model. Eventually, the model will be used in real-data experiments. The model will be implemented on the CYBER-205 computer system, and simple idealized experiments will be used to evaluate the model sensitivity to adjustable parameters, including resolution and lateral diffusion. The model will be tested with a symmetric vortex on an f-plane. Experiments will then be made with an initially symmetric vortex on a beta plane in an environment at rest.

6. Objective Analysis of the Hurricane and Its Environment

Goal

The major goal of this research is completion of the development of the objective HRD spline analysis scheme that assimilates data from the HRD synoptic-flow experiment and can incorporate data from a wide variety of platforms. Such platforms include Doppler radar, ODW's, NOAA WP-3D and other reconnaissance aircraft, rawinsondes, and satellites. This project represents an important link between HRD's ODW experiment and several HRD modeling experiments.

Accomplishments (FY-89)

A manuscript entitled "The Environment of Hurricane Debby (1982). Part II: Thermodynamic Fields" was submitted to the *Monthly Weather Review*. The manuscript describes thermodynamic budgets for Debby when it was near Bermuda and diagnostic estimates of rainfall using the Arakawa-Schubert cumulus parameterization. A study was made of midtropospheric vorticity advection (VA) fields using the HRD analyses scheme and observations from the Hurricane Debby (1982), Josphine (1984), Gloria (1985), Emily (1987), and Florence (1988) cases. These analyses showed a dipole in the VA fields that pointed approximately along the storm motion vector when the fields were analyzed at a certain scale that was determined from scaling arguments. These results were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in San Diego in May 1989.

Three-dimensional wind analyses were completed for the second Hurricane Josephine day (0000 UTC 11 October 1984). Diagnostic studies of the variability of the azimuthally averaged flow around the storm were made for the first two Hurricane Josephine cases. The "environmental steering" was shown to vary strongly, both as a function of height and radius. The nested, barotropic, spectral hurricane track prediction model (VICBAR) was used to evaluate the importance of various atmospheric layers in determining the motion of Hurricane Josephine. Model performance was critically dependent upon the layers chosen for initialization, and the best VICBAR forecasts were obtained by initializing the model with the layers whose flow was most consistent with the current storm motion. These results were presented at the AMS *18th Conference on Hurricanes and Tropical Meteorology*.

Analysis of VAS-ODW comparisons for 1 September 1988 continued. This a collaborative effort with the University of Wisconsin and the NOAA/National Environmental Satellite, Data, and Information Service.

A significant enhancement was made to the analysis scheme that permits "bogus" data values to be determined from a Barnes (scan) analysis of radial and tangential winds. The user can perform a nested analysis in r-theta coordinates near the storm center to fill gaps in the data coverage. This bogussing procedure greatly improved the Hurricane Gloria analyses within 400 km of the center.

Plans (FY-90)

A manuscript that describes the VAS-ODW comparisons from the 1987 and 1988 field experiments will be completed and submitted for publication.

Three-dimensional wind analyses for the third Hurricane Josephine (1984) case will be completed. Work will begin on a manuscript describing the wind analyses for the three Hurricane Josephine synoptic-flow experiments. Results of VICBAR forecasts for Hurricane Josephine and their relationships to environmental steering will also be described.

Three-dimensional wind analyses for the Hurricane Gloria synoptic-flow experiment will be completed. This will be the most complete multiscale, three-dimensional wind analysis of a hurricane and its environment constructed to date. The analyses will be used in a variety of diagnostic studies and to initialize a series of VICBAR experiments.

Work will begin on the analysis of wind data for the Hurricane Florence (1988) and Emily synoptic-flow experiments.

7. Tropical Climate Studies

Goal

The goal of this work is the establishment of a climatology and time history of quasi-steady and propagating disturbances over the tropical Atlantic. The relationship of the long-term variability of the winds to climatic fluctuations and to hurricane cycles will be studied.

Accomplishments (FY-89)

A paper on the relationship of the **q**uasi-**b**iennial **o**scillation (QBO) to Atlantic tropical storm activity was published in the July 1989 *Monthly Weather Review*. Monthly averaged 30- and 50-mb zonal winds at Balboa, Canal Zone, were used to determine objectively the relationship of the QBO to Atlantic tropical storm activity during 1952-86. The largest correlations between storm activity and the 30-mb wind are found in June, which is 3 months before the peak of the hurricane season. Extrapolation and direct calculation confirm a near in-phase relationship between tropical storm activity and the zonal wind at ~50 mb.

Zonal winds filtered to remove periods less than ~1 year were used to establish correlations between the QBO and tropical storm activity for 1955-83 that are independent of the month considered. A correlation at 30 mb was established with a conservative estimate of true skill, from both in-phase and out-of-phase information, that explains 30% of the variance in storm activity. The skill is much greater than that estimated from seasonal classifications of the QBO. The statistics are resilient to removal of the effects of the El Niño cycle. When El Niño years are explicitly excluded, the true skill explains an estimated 32% of the variance.

Physical mechanisms possibly responsible for the observed association were discussed in light of these results. A mechanism for the observed correlation was suggested that emphasizes the difference between lower tropospheric steering and the lower stratospheric zonal wind.

The results of this research were presented in seminars at at Florida State University and the Geophysical Fluid Dynamics Laboratory. A new study was 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 these cycles. Preliminary results established the hurricane cycles associated with the oscillation using records since 1899. The cycles were related to an objective index of the global oscillation, as well as Atlantic tropical wind variability, using data from 1977-84 when wind observations from NHC's tropical analysis were used after being filtered to remove periods less than ~15 days.

Plans (FY-90)

The study of the 30- to 60-day period variability of Atlantic tropical winds and hurricane cycles will be continued. Spectra will be made of the Atlantic tropical winds for selected regions, and maps of energy in the 30- to 60-day band will be made at both lower (near-surface) and upper (near 200-mb) levels. Winds for 1980-89, filtered to isolate the 30-60 day band, will be used to perform a regional **e**mpirical **o**rthogonal **f**unction (EOF) analysis over the Atlantic area. A Hilbert transform will be used to study the amplitude and phase behavior of the dominant EOF modes. The dominant modes will be related to an objective index of the global oscillation.

8. Tropical Cyclone Awareness Research

Goal

The goal of this work is the development and testing of educational strategies, programs, and supporting materials that are designed to create/enhance awareness of tropical cyclones and to promote preparedness and mitigation efforts in tropical-cyclone-prone areas.

Accomplishments (FY-89)

A computer-assisted instructional (CAI) component (cognitive module) of the cognitive and affective learning model (CALM) model was developed. Instructional units and pre-/post-tests were developed and reviewed by HRD scientists and NHC forecasters. CAI units and tests were modified in accordance with the suggestions of these reviewers.

A simple scheme was designed to test the hypothesis that "tropical cyclone awareness was created/ enhanced by the CAI educational treatment." Teachers from three local schools (two middle schools and one senior high school) participated in the program that involved: (1) pretest, no educational treatment, post-test; (2) pretest, standard educational treatment (a lecture), post-test; or (3) pretest, cognitive/affective treatment, post-test).

A sufficient data set (52 students) was assembled to test the hypothesis that the cognitive component of the CALM model increased the students' level of hurricane awareness. (Increased hurricane awareness was defined as the positive difference in the student's pre- and post-test scores.) It was concluded that exposing students to the cognitive module of CALM increased their hurricane awareness.

The CAI units went through several iterations. Units were reviewed several times by meteorologists at AOML/HRD and NHC. The text and accompanying illustrations in the CAI units were corrected where necessary, and information that proved to be confusing to the middle and high school students was modified.

Plans (FY-89)

Valuable suggestions and comments were received from teachers and students during the proof-of-concept testing program. These comments will be used in an effort to improve the program.

9. Storm Surge

Goal

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

Accomplishments (FY-89)

Hypothetical storm surge simulations were completed for the Biscayne Bay and Cape Canaveral, Florida, basins. Preliminary atlases were also completed for these basins.

Plans (FY-90)

Hypothetical hurricane storm surge simulations will be made for Charlotte Harbor and Apalachicola, Florida. Preliminary atlases for these basins will be completed.

10. GALE

Goal

The goal of this research is the description of rainbands observed during the Genesis of Atlantic Lows Experiment (GALE) and an understanding of the influence of the Gulf Stream on their formation and evolution.

Accomplishments (FY-89)

HRD collected data from NWS radars during GALE, a midlatitude field program, in 1986. In this project, we examined important mesoscale precipitation features that occurred during GALE, particularly the influence of the Gulf Stream on rainband occurrence.

In early October 1988, a paper on GALE rainbands was presented at the GALE/CASP (Canadian Atlantic Storms Program) Workshop at Val Morin, Quebec. The rainbands were divided into groups that were relative to the western edge of the Gulf Stream: western rainbands and Gulf Stream rainbands. Rainbands formed most often in the warm sector ahead of frontal systems; those warm-sector rainbands that formed > 400 km ahead of cold fronts almost always formed over Gulf Stream waters. Most of the western rainbands never crossed the Gulf Stream. Of those that did, few intensified.

The rainbands varied in reflectivity from weak bands with echoes < 30 dBZ to squall lines with peak reflectivities > 50 dBZ. The **m**anually **d**igitized **r**adar (MDR) data for GALE were obtained. For each rainband, maxima MDR > 30 dBZ were most numerous within 20 km of the western edge of the Gulf Stream. This region was just north of the highest values of cloud-to-ground lightning activity observed during GALE.

GALE sounding data were examined to find the soundings that were most representative of the rainband environments when the radar echoes first appeared. From these soundings, band-relative winds and stability parameters were computed. One interesting result was that two significantly different subsets of Gulf Stream rainbands were identified: slow-moving bands, with line-normal speeds $< 3 \text{ m s}^{-1}$ and fast-moving bands, moving $> 7 \text{ m s}^{-1}$. The lifted index was significantly lower for the fast-moving bands and the steering level (the level at which the band-relative winds most nearly paralleled the band) was higher. The slow-moving bands were probably more closely tied to marine boundary-layer circulations.

Plans (FY-90)

A GALE manuscript that describes these results will be submitted for publication.

11. EMEX

Goal

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-89)

Two-thirds of the airborne Doppler data for the EMEX research flights have been merged onto tapes that also contain reflectivity data. The merge tapes have been sent to the University of Washington (UW) for subsequent vertical incidence and pseudo-dual-Doppler analysis. UW scientists have converted NCAR software for use in Doppler analysis on their computer system. Software packages have been developed to look at the vertical incidence and horizontal data. This allows examination of the vertical velocity and divergence profiles from the raw Doppler data from one leg at a time without requiring a pseudo-dual-Doppler analysis.

The Doppler data in convective regions show deep, broad, up- and downdrafts with peak vertical motions of 10 m s^{-1}. The strongest drafts appear to be above the height of the 0°C isotherm. Upper level downdrafts, stronger than the uncertainty in the particle fallspeeds, were frequently observed in intense convective regions. These strong, upper level, up- and downdrafts may play an important role in the mass budget of the tropical mesoscale convective systems.

The vertical incidence and pseudo-dual-Doppler techniques give qualitatively similar results when averaged over large domains. However, the vertical incidence method has much better spatial and temporal resolutions and thus shows narrower drafts than those obtained from the pseudo-dual-Doppler method.

Mean profiles of vertical velocity were computed for two Doppler analysis domains. The convective region profile was positive at all altitudes > 1 km with a peak of 1.5 m s^{-1} at 7.5 km altitude for a domain of 400 km^2. Over an area of 1600 km^2, the stratiform region profile showed a change from negative vertical velocities (~ -20 cm s^{-1}) below 4.5 km altitude (the height of the 0°C isotherm) to values slightly above 0 m s^{-1} (~5 cm s^{-1}) at altitudes > 4.5 km. Areas of stratiform precipitation showed a midlevel maximum in convergence and significant horizontal variation in particle vertical velocity, suggesting that these "stratiform" rain areas may contain weak convective circulations.

Plans (FY-90)

Merged Doppler tapes will be generated for the remaining one-third of the cases.

HRD scientists will continue their interaction with the UW group on the generation and interpretation of the pseudo-dual-Doppler and the vertical incidence analyses. In particular, an effort will be made to refine vertical velocity measurements from the vertical incidence data. The refinements will concentrate on improvements to the reflectivity/fallspeed relationships for ice crystals.

12. Hurricane Energetics and Budget Study

Goal

A study of the energy balance of the hurricane is fundamental to increased understanding of the rules governing the intensification and maintenance of the storm circulation. The goal of this research is to compute the budgets of mass, total heat, water substance, kinetic energy, and absolute angular momentum for one or more hurricanes. To do this, it is necessary to measure the detailed kinematic and thermodynamic structure of a hurricane over a radius of 240 nmi with Doppler radar and ODW's and to map the radar echo in three dimensions.

Previous energy budget studies of hurricanes were based upon data that were available in the 1960's. There have been significant advances in observing capabilities since then. Recently developed observational capabilities, particularly the airborne Doppler radars and ODW's allow a resolution and three-dimensional coverage over a large volume of the hurricane that was heretofore unattainable. This work will exploit these vastly improved observational tools to acquire a data set for the analysis hurricane budgets.

Accomplishments (FY-89)

The capability of the airborne Doppler radar to measure the winds, both high in the outflow layer and in the boundary layer, will allow data to be gathered to address questions regarding the roles of generation, eddy importation, and exportation of angular momentum in storm intensification.

A feasibility experiment was conducted in Hurricane Gilbert on 11 September 1988. The success of the experiment was limited, because the Doppler radar was inoperative on the outer aircraft, and the ODW's did not work well, particularly on the south side of the storm.

Plans (FY-90)

The full experiment will be attempted in 1989 or 1990. If a successful experiment is accomplished in 1989, a major effort will be started to produce the necessary data analyses. This will require extensive Doppler editing and analysis, as well as analyses of flight-level, radar reflectivity, and ODW data.

The data set for Hurricane Gloria (1985) will continue to be used to test a variety of concepts and procedures.

13. 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 in the afternoon over the Florida peninsula in summer. The research uses routine operational data archived at the National Climatic Center and WP-3D aircraft observations obtained during HRD sea-breeze experiments in previous years. 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-89)

A manuscript that describes 23 July 1987, a summer day in south Florida without significant rainfall or radar echoes, was published in the March 1989 *Monthly Weather Review*. Such a day is rare, occurring < 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. A seminar on the sea breeze research was presented at Florida State University on 21 February 1989.

Plans (FY-90)

A short climatological study of the interaction between the lake breeze of Lake Okeechobee and the sea breeze 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 the 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 WP-3D flights of 14 July 1982. On that day, the two WP-3D's flew perpendicular to the coastline near Naples to monitor the development of the sea breeze circulation. However, the sea breeze circulation and deep convection failed to develop near Naples because the Naples 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: Further Analysis of the Ice Phase in the Hurricane

Continued analysis of Hurricane Emily (1987) and Hugo (15 September 1989) has demonstrated strong electric field build-up near the eyewall to be associated with strong vertical velocities, > 10 m s^{-1}, at temperatures near -3°C. This characteristic is to be contrasted with much weaker electric fields and vertical velocities observed in Hugo (21 September 1989) where vertical velocities were ~5 m s^{-1} at ± 5°C. This suggests that microphysical processes were quite different in these situations, with depletion of liquid water by coalescence-induced precipitation in weaker updrafts at lower levels.

Analysis of a case study of an isolated convective tower has led us to conclude that in-situ particle transformation is dominant in precipitation formation. In particular, the precipitation flux is shown to be very sensitive to the density assumed for larger (mm) ice particles in computing precipitation flux (0.9 to 0.4 g cm^{-3}). This must be realistically represented in models of these events.

A charge-particle probe has been completed, mounted on the WP-3D, and undergone preliminary flight trials. Data were obtained on all flights in Hugo. The real-time display has been developed to show the number of charged particles > $\pm 10^{-14}$ C at 5 s update.

Related Publications

WILLIS, P. T., and J. Hallett. Microphysical measurements from an aircraft ascending with a growing isolated maritime cumulus tower. *J. Atmos. Sci.* (Submitted)

BLACK, R. A., and J. Hallett, 1989: Electrical and microphysical measurements in the hurricane eyewall. *J. Atmos. Sci.* (In preparation)

Related Work

Under the sponsorship of the National Science Foundation (Meteorology Division), laboratory studies have demonstrated that evaporation and melting of ice leads to particle break-up and charge separation. These processes may be of importance immediately inside the eyewall in descending, evaporating, cooled air as well as in specific regions of the melting layer.

2. National Center for Atmospheric Research

Principal Investigators:	Dr. Gary M. Barnes Dr. Margaret A. LeMone
Project Scientists:	Dr. Andrew Heymsfield Mr. Gregory Stossmeister Mr. Patrick Zimmerman

Project: Hurricane Rainbands: Meso- and Convective-Scale Structure

Tropical Storm Irma (1987)

During EMEX, the NOAA WP-3D, the NCAR Electra, and the COSSA F-27 probed a rainband in developing Tropical Storm Irma (1987) in the Gulf of Carpentaria. G. Barnes and B. Ryan (CSIRO) are using these aircraft, as well as radar and rawinsondes from nearby land stations, to assemble a view of the thermodynamic and kinematic structure of this 50-km-wide rainband, which is the principal region for convective activity in this asymmetric vortex.

The Irma data set provides us with the opportunity to examine a rainband in a tropical storm, where we may see if it plays an inhibiting or enhancing role in the intensification process of the cyclone. Previous results make a good case for convectively active rainbands modifying the thermodynamics of the inflow to the core and inhibiting intensification, but bands have also been identified as zones where the tangential wind is found to be a maximum. Rainbands may be the location where high tangential winds are created and, therefore, may be partly responsible for vortex spin-up.

Unlike other rainbands, this band has flow entering from both sides in the boundary layer. Convergence exists over a broad region of 50 km rather than the usual 10-20 km. There is not a strong cold pool present that would tend to focus the convergence along its boundary. A maximum of 16 m s^{-1} in the tangential wind component exists at 1.5 km MSL (mean sea level) in the central part of the rainband. The vortex is not well developed at this time; tangential winds decrease to 5 m s^{-1} by 5 km MSL. This finding counters the large-scale studies that suggest that the vortex develops aloft and builds downward.

A zigzag pattern completed by the WP-3D enables us to examine azimuthal variability at 5 km altitude. The resultant analyses from the in-situ data and the Doppler radar show that, as one proceeds down the band, the tangential wind increases by > 10 m s^{-1}. D-values reveal a pressure decrease of 1 mb downband; this low pressure does not seem to be the result of the band crossing through the concentric pressure pattern that is well developed in a mature cyclone. Barnes presented some of these early findings at the AMS *18th Conference on Hurricanes and Tropical Meteorology* in May 1989. J. GAMACHE provided considerable help with the Doppler analyses when G. Barnes visited HRD in the spring of 1989.

Tropical Storm Isabel (1985)

Analysis of the aircraft data that were obtained during a 3-day period in Tropical Storm Isabel (1985) shows the development of a second circulation center > 80 km from the original center. Over the past year, our research has been aimed at discerning the characteristics of the new center and exploring possible mechanisms by which it was created. The development of the new center appears to be correlated with the development of strong convection in an adjacent rainband. The new low is found beneath the downwind anvil from this convection and is associated with subsidence warming. One of the theories under consideration is that sustained subsidence beneath a stratiform anvil associated with deep convection induces a hydrostatic low near the surface. Since the pressure field is undergoing a constant forcing, the wind field may eventually adjust and a new circulation center could form. This hypothesis could also explain how the original low pressure forms in a developing tropical depression. A manuscript on this work is in preparation and should be submitted to *Monthly Weather Review* in 1990.

Program and Techniques Development

G. Stossmeister and T. Antoniou, with the help of J. GAMACHE, have written computer programs to read the original OAO [Office of Aircraft Operations (now AOC)] aircraft tapes. These programs allow scientists at NCAR, who work with a VAX computer system, to access any variable, whether it be in a raw or final form.

There is an initiative to link NCAR Doppler-radar programs with airborne radar and Doppler-radar data. The formats of the OAO radar tapes will be changed to universal format so the SPRINT and CEDRIC analysis packages, as well as the NCAR graphics, can be used. The completion of this project should allow many more people to analyze the valuable information obtained from the airborne radar system on the WP-3D's.

Measurement of Trace Gases in the Hurricane Environment

During the 1989 field season, hydrocarbon samplers were mounted on NOAA 42 to make measurements in the lower troposphere of hurricanes. Instrument problems have been corrected and P. Zimmerman and M. A. LeMone hope to have some observations to analyze from Hurricane Hugo (1989).

Microphysics of Hurricanes

P. WILLIS and A. Heymsfield are examining the microphysical trajectories in Hurricanes Norbert (1984) and Emily (1987). In their study, a detailed microphysical model of hydrometeor evolution is being combined with the three-dimensional flow fields observed with Doppler radar to produce a spectrum of hydrometeor trajectories. The microphysical model deals with the growth of seven initial hydrometeor types, including single crystals, aggregates, graupel and hail, and water drops. The relationship between hydrometeor inputs from convection and the development of regions of stratiform precipitation is the theme of the research. An abstract has been submitted to the 1990 AMS *Joint Cloud Physics/Atmospheric Radiation Conference*.

Related Publications

Barnes, G. M., 1989: Summary of the *18th Conf. on Hurricanes and Tropical Meteorology*, May 16-19, 1989, San Diego, Calif. *Bull. Amer. Meteorol. Soc.* (In preparation)

Barnes, G. M., M. A. LeMone, J. GAMACHE and G. J. Stossmeister, 1988: Convective cell structure in a hurricane rainband. *Mon. Weather Rev.* (In preparation)

Barnes, G. M., E. J. Zipser and B. Ryan, 1989: Rainband structure in developing Tropical Cyclone Irma (1987). *Ex. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 151-152.

Stossmeister, G. J., and G. M. Barnes, 1989: Low-level structure of a nondeveloping tropical storm: Isabel (1985). *Ex. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 83-84.

Stossmeister, G. J., and G. M. Barnes, 1990: On the development of a second circulation center within Tropical Storm Isabel (1985). *Mon. Weather Rev.* (In preparation)

WILLIS, P. T., and A.J. Heymsfield, 1989: Structure of the melting layer in mesoscale convective system stratiform precipitation. *J. Atmos. Sci.,* 46 (13), 2008-2025.

3. Science Applications International Corporation

Principal Investigator: Mr. Charles J. Neumann

NHC Co-Investigator: Mr. Colin J. McAdie

Project: Revisions to the NHC83 Model

NHC83 is a statistical-dynamical model that became operational at the National Hurricane Center for the 1983 hurricane season. The model was developed in the "Perfect-Prog" mode, but, in the operational mode, utilizes numerically forecast deep-layer-mean geopotential height fields as derived from the National Meteorological Center medium range forecast (MRF) model. Based upon verification statistics over the 6-year period from 1983-88, as well as other "yardsticks" of model performance, such as timeliness, availability and reliability, NHC83 has consistently outperformed other NHC models.

Two approaches for further improvement to the model are being investigated. The first is to retain the deep-layer-mean height fields as the main source of predictive information, but to completely restructure the model and correct certain deficiencies that had been noted over the past 6 years of operational performance. These deficiencies include such factors as (1) too much sensitivity to biases in the MRF model, (2) a developmental data set that did not include data in the deep tropics, (3) a too-rigidly defined stratification system, and (4) nonoptimal location of predictors.

Such a model, to be referred to as NHC83R, has been completed and, based upon developmental data, the model should outperform the NHC83 model, particularly for storms embedded in the easterlies. Only slight improvement has been noted on storms after recurvature. An operational version of the model is being tested on 1989 Atlantic tropical cyclones.

The second approach is to abandon the use of deep-layer-mean heights and to redevelop the model using deep-layer-mean winds as the main source of predictive information. A preliminary model (NHC89) has been developed and, based upon developmental data, the model is a substantial improvement over the older NHC83 model for storms embedded in the easterlies. However, as was the case for the NHC83R model, much less improvement is noted after recurvature.

Although the wind model appears promising, a serious problem is noted when the model is run in an operational mode. Predictive information is located very close to the storm center and inconsistent treatment of the storm vortex in the initial analyses, as well as in the numerical prognoses, seriously compromises the ability to statistically extract this information. In the height model (NHC83 and NHC83R), this is much less of a problem, because predictive information is located at substantial distances from the storm center.

In view of the problems, further development of the NHC89 model is being held in abeyance until a suitable filter can be developed for removal of the tropical cyclone vortex from analyses and prognoses. Testing of various filters is under way.

Related Publications

Neumann, C. J., 1988: The National Hurricane Center NHC83 Model. NOAA Tech. Memo. NWS NHC 41, National Hurricane Center, Coral Gables, Fla., 44 pp.

Neumann, C. J., and C. J. McAdie, 1989: Revisions to the National Hurricane Center NHC83 Model. (Submitted to NHC as a NOAA Tech. Memo.)

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 investigated the evolution of the outflow layer in Hurricane Elena (1985) as the storm went through a series of track and intensity changes. The results were published in the *Journal of the Atmospheric Sciences*. This paper reported calculations made from objectively analyzed outflow-layer winds using rawinsonde and upper troposphere cloud motion vectors.

Following this work, we looked at the three-dimensional structure of the interactions between Elena and the middle latitude trough using gridded analyses from the European Center for Medium Range Weather Forecasting (ECMWF). The resulting manuscript was submitted to the *Journal of the Atmospheric Sciences*. The abstract for that paper follows:

Abstract. The vertical structure of the interaction of Hurricane Elena (1985) with a baroclinic wave was evaluated using analyses from the European Center for Medium Range Weather Forecasting. Angular momentum fluxes by azimuthal eddies at 200 mb were like those seen in Part I, with a large region of outflow-layer inward cyclonic flux, but highly localized regions of momentum flux convergence at progressively smaller radii prior to the major secondary deepening of the storm. These fluxes decayed rapidly above and below the outflow layer. Eddy heat fluxes showed maximum cooling in the middle and upper troposphere and warming in the lower stratosphere, reflecting the temperature structure of the baroclinic wave as it moved into the hurricane volume.

The response of the hurricane vortex to the fluxes of heat and angular momentum was determined by solution of Eliassen's balanced vortex equation. Prior to the secondary deepening, the eddies drove an in-up-out circulation, which shifted inward from the 500-km radius to the hurricane core over 24 h. Eddy heat fluxes contributed to the induced circulation in the same manner as momentum fluxes near the core, but with smaller magnitude and areal coverage. The intensification of the storm was interpreted as a geostrophic adjustment response to the eddy fluxes. The observed spin-up of the storm, which began at upper levels and spread to middle and then lower levels over 24 h, provided support for this view.

When eddy forcing reached inner radii, it appears to have excited formation of the inner core secondary wind maximum, which was directly associated with deepening of the storm. Because the overall magnitude of the induced circulation was much weaker than that observed, it is likely that diabatic feedback played a major role in this process. The eddy forcing is thus viewed as organizing the diabatic sources in such a way as to release internal instabilities of the system.

Related Publications

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy angular momentum fluxes. *J. Atmos. Sci.*, 46 (8), 1093–1105.

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part II: Vertical structure and response of the hurricane vortex. *J. Atmos. Sci.* (Submitted)

Molinari, J., and D. Vollaro, 1989: Interaction of a hurricane with a baroclinic wave. *Ex. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 16–19, San Diego, Calif., 50–51.

5. State University of New York at Albany

Principal Investigator: Dr. John Molinari

Project Scientist: Mr. David Vollaro

Project: Intensity Changes in Hurricane Allen

We have completed the outflow-layer objective analyses of Allen (1980). Unlike in the Hurricane Elena (1985) case, we had to use ECMWF analyses as first-guess fields, because some empty octants appeared in our data set at outer radii. Nevertheless, the overall data set was excellent because it was supplemented by enhanced cloud motion vectors determined many years ago by H. HAWKINS. The combination has produced a detailed look at the outflow-layer evolution during the many intensity fluctuations in Allen. Simultaneously, we have interpolated ECMWF analyses to cylindrical grids centered on the storm to give us a measure of the vertical structure.

Four major outflow events occurred in Allen. Three were associated with the ends of sustained periods of deepening, as would be expected as enhanced convection produced enhanced outflow. The fourth occurred prior to the second deepening (which is the first *reintensification* after initial development). Much like in Elena, this outflow maximum reflects inward fluxes of cyclonic angular momentum. In Allen, these fluxes arise because the storm is moving under a cyclonic vorticity maximum aloft. This maximum represents a cyclonic heat zone between the outflow layers of Allen and a decaying eastern Pacific hurricane. Balanced vortex solutions show that an upward motion maximum shifted inward to the storm core at the time of formation of the secondary eyewall. Thus, although the phenomenon producing the momentum forcing differs markedly from the middle latitude trough in the Elena case, the response is strikingly similar. We conclude that the first reintensification of Allen was driven by interactions with the upper tropospheric environment.

The other reintensification of Allen, which began on 8 August 1200 UTC, was not accompanied by upper level forcing. Thus, initially, we were faced with the unsatisfying prospect that some secondary intensifications are produced by external forcing and others occur on their own, even though the result, a contracting outer eyewall, looks the same. Recently, however, while examining vertical cross sections of radial velocity, we found an inflow "surge" whose structure resembled that found in Hurricane Agnes of 1972.[2] The surge first appeared near the 1800 km radius and propagated inward over 24 h. Simultaneous with its reaching the storm core, rapid deepening began. All of these characteristics are identical to the surge in Agnes. We have not yet determined whether the surge had similar asymmetry to the earlier one.

[2] J. Molinari, and S. Skubis, "Evolution of the surface wind field in an intensifying tropical cyclone," *J. Atmos. Sci.*, 42:2865–2879 (1985).

Because this inflow surge was found using ECMWF analyses, whose radial velocity is suspect, some caution is needed in interpretation. We compared the ECMWF radial velocity in Allen to the objectively analyzed winds at 200 mb, where we had the highly detailed data set, including the HAWKINS cloud vectors. We found considerable errors in magnitude of the radial velocity, higher than those in Elena, because the Allen analyses were from 1980, prior to the development of diabatic initialization at ECMWF. Nevertheless, we found that the timing and positioning of each outflow maximum was accurately reproduced. We conclude that the surface-layer inflow surge is likely to be realistic, but simply underestimated in magnitude.

Despite considerable effort in the Agnes case, we (Molinari and Skubis) were unable to determine a cause for the inflow surge. We were hampered by the lack of sufficient data at any level above the surface. In the current case, we have seven levels of analyses, and our main focus will be on determining the cause of the inflow surge in Allen. Having now seen this phenomenon in three case studies, we believe it may be of fundamental importance in understanding how hurricanes intensify.

One striking phenomenon in Allen is the symmetry of the pressure changes during the three major intensity fluctuations. The direct reason for this has been detailed by H. WILLOUGHBY. We now believe that these secondary eyewalls were forced by an external mechanism that drove an in-up-out circulation that shifted inward to the storm core. Our working hypothesis is that all reintensifications of tropical cyclones have an external cause. We will continue to develop our thinking using the Allen case study.

Related Publications

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy angular momentum fluxes. *J. Atmos. Sci.*, 46 (8), 1093-1105.

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part II: Vertical structure and response of the hurricane vortex. *J. Atmos. Sci.* (Submitted)

Molinari, J., and D. Vollaro, 1989: Interaction of a hurricane with a baroclinic wave. *Ex. Abst.. 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 50-51.

6. University of Massachusetts

Principal Investigator: Dr. Calvin T. Swift

Project Scientists: Ms. Karen St. Germain
Mr. Jonas Aleksa

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

This program uses an SFMR to remotely measure ocean surface wind speed and rain rates in hurricanes. The bulk of the effort during the past year focused on software development of the wind-speed/rain-rate algorithm to achieve a real-time wind speed data product. This work appears to be successful, so that the real-time winds will be available for the 1990 hurricane season.

During the winter of 1989, the SFMR was shipped to Brunswick, Maine, for reinstallation on the NOAA WP-3D for use in the ERICA program. The scientific purpose was examination of the wind speed algorithm's response to a cold ocean. Although data are still being analyzed, the preliminary results indicate that the algorithm is relatively insensitive to changes in sea-surface temperature.

The University of Massachusetts has developed a scanning C-Band precision radar, or scatterometer, to remotely measure the wind vector over the ocean. The scatterometer has been flight-tested in the NASA C-130. In early 1990, we will discuss, with NOAA/OAO personnel, the installation of a scatterometer on a NOAA aircraft for hurricane research.

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 .

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

Tanner, A. B., 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: Mr. Brian Mapes
Mr. Chungli Wang

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

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

Major articles have been submitted 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 Hurricane 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 radar reflectivity and Doppler radar wind fields.

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 has been completed. 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 kinematic information 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 derive vertical air motions. Preliminary results indicate that the vertical motion profiles can be indicated reasonably well by pseudo-dual-Doppler analysis. The stratiform regions have mesoscale updraft aloft and mesoscale downdraft below, as in other regions of the world. Convective regions have maximum vertical motions at upper levels, thus being somewhat different than in regions previously investigated, especially the eastern tropical Atlantic.

Vertical incidence Doppler radar data also indicates intense updraft structure at upper levels. This result appears to be new and is being vigorously examined. Convection was often arranged in squall lines, and the kinematic data are being examined in relation to squall structure. The convective line areas were often observed to collapse into stratiform structures and kinematic data are being examined in some of these collapsing zones. Such data sets have not been obtained previously.

The kinematic data are being examined in relation to the momentum budget. Vertical and horizontal wind components from the Doppler radar are being examined in relation to flight level pressure fields (derived from D-values). All of this work is in progress and will be reported over the next year.

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 form 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, Germany, 711-713.

Houze, R. A., Jr., 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Quart. J. Roy. Meteor. Soc.*, 115 (487), 425-461.

Houze, R. A., Jr., 1988: Convective and stratiform precipitation in the tropics. *Tropical Rainfall Measurements*. J. S. Theon and N. Fugono, eds., A. Deepak Publ., Hampton, Va., 27-35.

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, Wash.

Houze, R. A., Jr., F. D. MARKS, JR., J. F. GAMACHE 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, Germany, 708-710.

Houze, R. A., Jr., F. D. MARKS, JR., J. F. GAMACHE and R. A. BLACK 1989: Dual-aircraft investigation of the inner core of Hurricane Norbert: Part II, Patterns of fallout and growth of ice particles. *J. Atmos Sci.* (Submitted)

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. Abst., 17th Conf. on Hurricanes and Tropical Meteorology*-AMS, Miami, Fla., 347-350.

MARKS, F. D., JR., R. A. Houze, Jr. and J. F. GAMACHE, 1989: Dual-aircraft investigation of the inner core of Hurricane Norbert: Part I, Kinematic and thermodynamic structure. *J. Atmos. Sci.* (Submitted)

Appendix A: Publications[3]

A.1 In Print

[1] Barnes, G. M., E. J. Zipser and B. Ryan, 1989: Rainband structure in developing Tropical Cyclone Irma (1987). Research supported by NOAA Grant 45-WCNR-5-00388. *Ext. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 151-152.

[2] BLACK, M. L., 1989: Signal loss of WSR-57 radars as a function of range in tropical cyclones. *Prepr., 24th Conf. on Radar Meteorology*-AMS, March 27-31, Tallahassee, Fla., 514-517.

[3] BLACK, M. L., and F. D. MARKS, JR., 1989: Concentric eyewalls in Hurricane Gilbert (1988). *Ext. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 224-225.

[4] 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. and Ocean. Tech.*, 5 (6), 683-698.

[5] BLACK, P. G., L. K. Shay, R. L. Elsberry and J. D. Hawkins, 1989: Response of the Gulf of Mexico to Hurricane Gilbert. *Ext. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 226-227.

[6] BURPEE, R. W., 1989: A summer day without significant rainfall in south Florida. *Mon. Weather Rev.*, 117 (3), 680-687.

[7] BURPEE, R. W., 1989: Forecaster biography - Gordon E. Dunn: Preeminent forecaster of mid-latitude storms and tropical cyclones. *Wea. and Forecast.* 4 (4), 573-584.

[8] BURPEE, R. W., 1989: Radar characteristics of hurricanes. In Federal Meteorological Handbook No. 11, *Doppler Weather Radar Observations*. Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

[9] BURPEE, R. W., and M. L. BLACK, 1989: Temporal and spatial variations of precipitation near the centers of two tropical cyclones. *Mon. Weather Rev.*, 117 (10), 2204-2218.

[10] BURPEE, R. W., M. L. BLACK and F. D. MARKS, JR., 1989: Vertical motions measured by airborne Doppler radar in the core of Hurricane Elena. *Ext. Abst., 18th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 16-19, San Diego, Calif., 69-70.

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A.2 Accepted

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[59] POWELL, M. D., 1990: Boundary-layer structure and dynamics in outer hurricane rainbands. Part II: Downdraft modification and mixed-layer recovery. *Mon. Weather Rev.*, 118.

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[63] WILLOUGHBY, H. E., 1990: Gradient balance in tropical cyclones. *J. Atmos. Sci.*, 47.

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A.3 Submitted

[65] DEMARIA, M.: Normal mode initialization in tropical cyclone models. *J. Atmos. Sci.*

[66] FRANKLIN, J. L., C. S. Velden, J. KAPLAN and C. M. Hayden: Some comparisons of VAS and dropwindsonde data over the subtropical Atlantic. *Mon. Weather Rev.*

[67] Houze, R. A., Jr., F. D. MARKS, JR., J. F. GAMACHE 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.*

[68] LORD, S. J., and J. L. FRANKLIN: The environment of Hurricane Debby (1982). Part II: Thermodynamic fields. *Mon. Weather Rev.*

[69] 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.*

[70] Molinari, J., and D. Vollaro: External influences on hurricane intensity. Part II: Vertical structure and response of the hurricane vortex. (Research supported by NOAA Grant 50-WCNR-9-06080.) *J. Atmos. Sci.*

[71] Neumann, C. J. , and C. J. McAdie: Revision to the National Hurricane Center NHC83 model. (Research supported by NOAA Grant 50-DSNC-8-00141.) NOAA Tech. Memo. NWS NHC.

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[73] WILLOUGHBY, H. E.: Linear normal modes of a moving, shallow-water barotropic vortex. *J. Atmos. Sci.*

A.4 In Preparation

[74] Barnes, G. M., M. A. LeMone, J. GAMACHE, and G. J. Stossmeister: Convective cell structure in a hurricane rainband. *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. Oceanog.*

[76] BLACK, R. A., and J. Hallett: Electrical and microphysical measurements in the hurricane eyewall. *J. Atmos. Sci.*

[77] DODGE, P. P.: Rainbands and the Gulf Stream During the GALE Field Program. *Mon. Weather Rev.*

[78] GAMACHE, J. F.: A simple method for correcting in-cloud radiometric temperature measurements. *J. Atmos. and Ocean. Tech.*

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

[80] Tanner, A. B., 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.*

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

Appendix B: Presentations

B.1 AOML Seminars Presented by HRD Staff and Visitors

1988

October 6	Dr. Takashi Ohshima (Meteorological Satellite Center, Tokyo): "Estimation of Ocean Surface Wind for a Typhoon From GMS Cloud Motion Winds"
October 13	Mr. Jeffrey Masters (NOAA/Office of Aircraft Operations): "Navigational Problems on NOAA's WP-3D Aircraft"
October 27	Dr. T. N. Krishnamurti (Florida State University): "Hurricane Prediction With a High-Resolution Global Model" (RSMAS/MPO Seminar Series)

1989

January 9	Dr. Makut Mather (NOAA/National Meteorological Center): "NMC's Quasi-Lagrangian Hurricane Model"
January 13	Dr. David Atlas (NASA/Goddard Space Flight Center): "The Estimation of Convective Rainfall by Area Integrals and Storm Heights"
March 22	Dr. Eugene W. McCaul, Jr. (University of Oklahoma, CIMMS): "Dynamics of Simulated Convective Storms in Hurricane Environments"
April 10	Dr. John Hallett (University of Nevada, Desert Research Institute): "Evaporation and Melting of Ice Particles in the Atmosphere"
May 11	Dr. Geoffrey Austin (McGill University): "The Statistical Properties of Florida Rainfall and Their Impact on Measurement Accuracy"
May 22	Dr. Lance F. Bosart (State University of New York at Albany): "Environmental Factors in the Nondevelopment of a Tropical Disturbance and the Development of Hurricane Diana (1984)"
June 6	Mr. Charles J. Neumann (Science Applications International Corporation): "Status of Revisions to the NHC83 Prediction Model (NHC89)"
June 7	Dr. Fred Sanders (Massachusetts Institute of Technology, retired): "An Overview of the ERICA Project" (MMS Meeting)
June 7	Dr. William M. Gray (Colorado State University): "Long-Term Variations of the Tropical West Pacific Zonal Winds and Their Association With East Pacific Sea-Surface Temperature Variations" (CIMAS Seminar Series)
June 9	Dr. William M. Gray (Colorado State University): "Tropical Storm Genesis" (CIMAS Seminar Series)
August 28	Dr. John Molinari (State University of New York at Albany): "Intensity Changes in Hurricane Allen"
September 12	Dr. Wen-Chau Lee (National Center for Atmospheric Research): "The Evolution and Structure of the Bow Echo/Microburst Event" (CIMAS Seminar Series)

B.2 AOML Informal Research Reports Presented by HRD Staff

1988

November 15	Mr. PAUL T. WILLIS: "Trajectories of Hydrometeors in a Hurricane"
November 22	Dr. ROBERT W. JONES: "A Climatology of Tropical Data at the ATOLL and 200-mb Levels"
December 13	Dr. MARK D. POWELL: "The Relationship of Hurricane Flight-Level Wind Measurements to Winds Measured by NOAA's Oceanic Platforms"

1989

March 7	Dr. JOHN F. GAMACHE: "A Description of the Water Budget in Hurricane Norbert (1984)"
March 21	Dr. LLOYD J. SHAPIRO: "Vortex Evolution on a Beta Plane"
April 4	Dr. HUGH E. WILLOUGHBY: "Linear Normal Modes of a Moving, Shallow-Water Vortex"
April 18	Dr. FRANK D. MARKS, JR.: "Air Parcel and Precipitation Trajectories in Hurricane Norbert (1984)"
April 25	Dr. KATSUYUKI V. OOYAMA: "Modeling Physical Processes in a Spectral Model"
May 9	Mr. JAMES L. FRANKLIN: "Objective Analyses of Hurricane Josephine (1984)"
May 23	Dr. MARK DEMARIA: "The Effect of Omega Dropwindsonde Data on Barotropic Hurricane Track Forecasts"
May 30	Dr. ROBERT W. BURPEE: "Contrasting Relationships Between Surface and Flight-Level Winds in Two Tropical Cyclones"

B.3 HRD Informal Research Reports

1989

January 18	Dr. STEPHEN J. LORD: "A Hurricane Analysis Potpourri"
January 23	Mr. ROBERT A. BLACK: (a) "Z-M Relationships" and (b) "Strong Vertical Winds in Hurricanes"
March 6	Mr. PETER P. DODGE: "Precipitation Structure in Hurricane Elena (1985)"
April 3	Mr. VICTOR WIGGERT: "Storm Surge in Your Back Yard"
April 17	Mr. MICHAEL L. BLACK: (a) "Vertical Motion Statistics of the Inner Core of Hurricane Elena (1985) as Measured by Airborne Doppler Radar at Vertical Incidence" and (b) "Concentric Eyewalls in Hurricane Gilbert"
June 5	Mr. JOHN KAPLAN: "A Synoptic-Scale Evaluation of VAS Data Accuracy"

B.4 Presentations Given Outside by HRD Staff

1988

October 26	Dr. HUGH E. WILLOUGHBY: "Real-Time Analysis of Hurricane Gilbert (1988)" (at NWS/National Hurricane Center)
December 5	Dr. STEPHEN J. LORD: "Recent Analysis of the Hurricane Environment" (at NOAA/National Meteorological Center)

1989

February 21	Dr. ROBERT W. BURPEE: "Variations in South Florida's Summer Rainfall Associated With the Sea Breeze Circulation" (at Florida State University)
February 28	Dr. LLOYD J. SHAPIRO: "Large-Scale Influences on Atlantic Tropical Storm Activity" (at Florida State University)
April 7	Dr. PETER G. BLACK: "Review of Hurricane Surveillance Technology and Evaluation of U.S. Hurricane Warning System" (at U.S. House of Representatives, Committee on Science, Space, and Technology)
June 1	Dr. LLOYD J. SHAPIRO: "Large-Scale Influences on Atlantic Tropical Storm Activity" (at NOAA/Geophysical Fluid Dynamics Laboratory)
June 7	Dr. HUGH E. WILLOUGHBY: "The Dynamics of Tropical Cyclones" (at 23rd Annual Congress of the Canadian Meteorological and Oceanographic Society, Rimouski, Quebec)
June 22	Dr. ROBERT W. BURPEE: "Contrasting Relationships Between Surface and Flight-Level Winds in Two Tropical Cyclones" (at NOAA/National Meteorological Center)
June 23	Dr. MARK DEMARIA: "The Effect of Omega Dropwindsonde Data on Barotropic Hurricane Track Forecasts" (at NOAA/National Meteorological Center)
July 17	Dr. HUGH E. WILLOUGHBY: "Development of the Primary Circulation in Hurricanes" (at University of South Florida)
August 9	Mr. SIM ABERSON: "Preliminary Results From the VICBAR Hurricane Track Forecast Model for 1989" (at NWS/National Hurricane Center)
August 9	Dr. PETER G. BLACK: "Hurricane Dean Surface Winds" (at NWS/National Hurricane Center)
August 9	Dr. MARK DEMARIA: "An Overview of the VICBAR Track Forecast Model" (at NWS/National Hurricane Center)
August 9	Mr. JAMES L. FRANKLIN: "Environmental Steering and VICBAR Forecasts for Hurricane Josephine (1984)" (at NWS/National Hurricane Center)
August 9	Dr. HUGH E. WILLOUGHBY: "The Concentric Eyewall in Hurricane Gilbert (1988)" (at NWS/National Hurricane Center)
August 16	Dr. PETER G. BLACK: "SFMR Surface Winds: Recent Results" (at NOAA/Aircraft Operations Center)

Presentations (Continued)

August 16	Mr. ROBERT A. BLACK: "Unusually Strong Vertical Winds in a Caribbean Hurricane" (at NOAA/Aircraft Operations Center)
August 16	Dr. MARK DEMARIA: "The Use of Aircraft Observations in a Hurricane Track Forecast Model" (at NOAA/Aircraft Operations Center)
August 16	Dr. FRANK D. MARKS, JR.: "Velocity Track Display" (at NOAA/Aircraft Operations Center)
August 16	Dr. HUGH E. WILLOUGHBY: "The Concentric Eyewall in Hurricane Gilbert (1988)" (at NOAA/Aircraft Operations Center)

B.5 Special Presentations

Visit of Soviet Meteorologists to AOML/HRD

May 23, 1989

Dr. S. L. ROSENTHAL	"Overview of HRD's Research Activities"
Dr. R. W. BURPEE	"Overview of Field Program Activities in Hurricane Gilbert (1988)"
Dr. P. G. BLACK	"Response of the Gulf of Mexico to Hurricane Gilbert (1988)"
Dr. F. G. MARKS, JR.	"Concentric Eyewalls in Hurricane Gilbert (1988)"
Dr. H. E. WILLOUGHBY	"Real-Time Monitoring of Hurricane Gilbert (1988)"

B.6 Unpublished[4] Conference Presentations

25th Annual NOAA/NWS Hurricane Conference

December 6-8, 1988, Coral Gables, Florida

Mr. M. L. BLACK and Dr. F. D. MARKS, JR.	"A Radar Overview of Hurricane Gilbert (1988)"
Mr. R. E. Carbone and F. D. MARKS, JR.	"Velocity Track Display: A Real-Time Application for Airborne Doppler Radar Data in Hurricanes"
Dr. M. DEMARIA	"A Summary of the Hurricane Research Division Synoptic-Flow Experiment (1982-1988)"
Dr. M. D. POWELL and Dr. P. G. BLACK	"Hurricane Boundary-Layer Research: Recent Results and Future Prospects"

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

Unpublished Conference Presentations (Continued)

43rd Interdepartmental Hurricane Conference

January 10–13, 1989, Homestead AFB, Florida

Research Committee Meeting

Dr. P. G. BLACK and Dr. M. D. POWELL	"Surface Wind Estimation in Hurricanes: Recent Progress and Future Prospects"
Dr. M. DEMARIA	"The Impact of Omega Dropwindsonde Observations on Barotropic Hurricane Track Forecasts"
Messrs. J. L. FRANKLIN, J. KAPLAN and C. S. Velden	"A Comparison of VAS and ODW Data Around a Subtropical Cold Low"
Dr. S. J. LORD	"A Summary of the Hurricane Research Division Synoptic-Flow Experiment (1982–1988)
Dr. S. J. LORD	"Recent Topics in Data Analysis for the Hurricane Environment"
Dr. H. E. WILLOUGHBY	"Navy Tropical Cyclone Experiment"
Dr. H. E. WILLOUGHBY, Mr. W. P. BARRY, and Mr. M. E. RAHN	"Real-Time Monitoring of Hurricane Gilbert"

1989 National Hurricane Conference

April 4–7, 1989, Coral Gables, Florida

Dr. F. D. MARKS, JR.	"An Overview of Airborne Remote-Sensing Capabilities for Hurricane Reconnaissance and Research"

18th Conference on Hurricanes and Tropical Meteorology–AMS

May 16–19, 1989, San Diego, California

Mr. J. Bartlo	"A Case Study of the Environmental Conditions Associated With the Formation of Tropical Storm Diana in September 1984"
Dr. L. Bosart	"Frontogenetical Forcing Associated With a Heavy Rainstorm Along the Lower Texas Coast in September 1984"

12th Conference on Weather Analysis and Forecasting–AMS

October 2–6, 1989, Monterey, California

Dr. R. W. BURPEE	"Patterns of Convection Resulting From the Interaction of Lake and Sea Breezes in South Florida"

B.7 Workshop[5] Participation

GALE/CASP Workshop

October 2-7, 1988, Val-Morin, Quebec

Mr. P. P. DODGE — "A Survey of GALE Rainbands"

2nd Workshop on Regional Data Assimilation

CIMMS/NSSL/University of Oklahoma

March 6-9, 1989, Norman, Oklahoma

Dr. S. J. LORD and Dr. M. DEMARIA — "A Nested Analysis and Prediction System for Tropical Cyclone Track Forecasting"

PRE-STORM Workshop

September 11-13, 1989, Estes Park, Colorado

Mr. P. T. WILLIS

WMO International Workshop on Tropical Cyclones-II

November 27-December 8, 1989, Manila, Philippines

Dr. P. G. BLACK — "Overview of Hurricane Boundary-Layer Research"

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[5]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. ROBERT W. BURPEE	Fellow, American Meteorological Society
	Member, STORM Working Group on Mesoscale Convective Systems
Dr. MARK DEMARIA	Chairman, Miami Chapter, American Meteorological Society
	Member, Ad-Hoc Group for Tropical Cyclone Research
Mr. PETER P. DODGE	Secretary-Treasurer, Miami Chapter, American Meteorological Society
Mr. JAMES L. FRANKLIN	Member, Working Group for Upper Air Observations, Office of the Federal Coordinator for Meteorological Services and Supporting Research: Task Group for Digital Sonde Technology
Mr. HOWARD A. FRIEDMAN	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. JOHN F. GAMACHE	Member, NOAA Mesoscale Research Planning Team
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
	Member, Task Committee on Wind Damage Investigation, American Society of Civil Engineers
	Chairman, Research Committee, 1990 Interdepartmental Hurricane Conference
Dr. STANLEY L. ROSENTHAL	Fellow, American Meteorological Society
	Fellow, American Association for the Advancement of Science
	Member, ERL Aircraft Allocation Advisory Panel

Committee Memberships and Offices in Scientific Organizations (Continued)

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

Member, American Meteorological Society Committee on Tropical Meteorology and Tropical Cyclones

C.2 Awards

The **1989 ERL Outstanding Scientific Paper Award** was presented to Dr. FRANK D. MARKS, JR., and Dr. Robert A. Houze, Jr. (University of Washington) for "Inner Core Structure of Hurricane Alicia From Airborne Doppler Radar Observations," which appeared in the *Journal of the Atmospheric Sciences*, Vol. 44, No. 9, pp. 1296–1317 (1987).

The **1989 American Meteorological Society Banner I. Miller Award** was received by Dr. MARK DEMARIA for the best contribution to the science of hurricane and tropical weather forecasting published in a journal with international circulation. The paper, entitled "Tropical Cyclone Track Forecasting With a Barotropic Spectral Model," was published in the *Monthly Weather Review*, Vol. 115, No. 10, pp. 2346–2357 (1987).

C.3 CIMAS Visiting Scientist

Dr. Wen-Chau Lee

Affililation: National Center for Atmospheric Research, Boulder, Colorado

Research area: Real-time Doppler radar data processing

Assisting Dr. Frank D. Marks, Jr.

C.4 Guest Scientist

Mr. Li Tianming

Affiliation: Shanghai Typhoon Institute

Research area: Theoretical and modeling investigations of tropical cyclone prediction and analysis

Assisting Dr. Katsuyuki V. Ooyama

C.5 Graduate Student

Mr. Chris Landsea

Affiliation: Colorado State University, Boulder, Colorado

Research area: Real-time analysis of aircraft observations

Assisting Dr. Hugh E. Willoughby

C.6 Visitors

Dr. David Atlas, NASA/Goddard, Greenbelt, Maryland
Dr. Gary M. Barnes, National Center for Atmospheric Research, Boulder, Colorado
Dr. Francois Baudin, Centre de Recherches en Physique de l'Environement, Issy-les-Moulineaux, France
Dr. Lance Bosart, State University of New York at Albany
Dr. A. A. Chernikov, State Committee for Hydrometeorology and Control of the Natural Environment, Moscow, U.S.S.R.
Dr. Philippe Garnier, French Meteorological Service
Dr. Marc Gilet, French Meteorological Service
Dr. Willliam Gray, Colorado State University
Dr. Pierre Gregour, French Meteorological Service
Dr. John Hallett, Desert Research Institute, University of Nevada
Dr. Masahiro Hara, Meteorological Research Institute, Japan
Dr. William Heckley, European Center for Medium Range Weather Forecasts, Reading, England
Dr. John Lewis, National Severe Storms Laboratory, Norman, Oklahoma
Mr. Scott Maudia, The Pennsylvania State University
Dr. Eugene W. McCaul, Jr., University of Oklahoma
Dr. John Molinari, State University of New York at Albany
Dr. Frank Roux, Centre de Recherches en Physique de l'Environement, Issy-les-Moulineaux, France
Mr. Jose Sanchez-Sesma, Ministry of Agriculture, Vera Cruz, Mexico
Dr. I. G. Sitnikov, Hydrometeorological Research Centre, Moscow, U.S.S.R.
Mr. Gregory J. Stossmeister, National Center for Atmospheric Research, Boulder, Colorado
Dr. P. N. Svirkurnov, State Committee for Hydrometeorology and Control of the Natural Environment, Obninsk, Siberia
Dr. Jacques Testud, Centre de Recherches en Physique de l'Environement, Issy-les-Moulineaux, France
Dr. Misuzu Wada, Meteorological Research Institute, Japan
Mr. Vincent Wood, National Severe Storms Laboratory, Norman, Oklahoma
Dr. Masanori Yamasaki, Meteorological Research Institute, Japan

C.7 HRD Staff on September 30, 1989

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

James W. Trout, Assistant Program Manager
Supervisory Meteorologist

Aberson, Sim D.	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
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
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
Rahn, Edward	Computer Programmer
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

AAV	asymmetric absolute vorticity
AMS	American Meteorological Society
AOC	Aircraft Operations Center
AOML	Atlantic Oceanographic and Meteorological Laboratory
ASDL	aircraft-satellite data link
ATOLL	analysis of the tropical oceanic lower layer
AXBT	airborne expendable bathythermograph
AXCP	airborne expendable current probe
BSPMOE	Board on School and Popular Meteorological and Oceanographic Education
CAI	computer-assisted instruction
CALM	cognitive and affective learning model
CAPPI	constant altitude PPI (plan position indicator)
CARCAH	Chief, Aerial Reconnaissance Coordinator, All Hurricanes
CEAREX	Coordinated Eastern Arctic Experiment
CIMAS	Cooperative Institute for Marine and Atmospheric Science
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies
CLASS	Cross-Chain Loran-C Atmospheric Sounding System
CLIPER	climatology/persistence
DLM	deep-layer mean
DOC	Department of Commerce
DMSP	Defense Meteorological Satellite Program
ECMWF	European Center for Medium Range Weather Forecasting
EMEX	Equatorial Mesoscale Experiment
EOF	empirical orthogonal function
ERICA	Experiment on Rapidly Intensifying Cyclones over the Atlantic
ERL	Environmental Research Laboratories
FSSP	forward scattering spectrometer probe
GALE	Genesis of Atlantic Lows Experiment
GALE/CASP	Genesis of Atlantic Lows Experiment/Canadian Atlantic Storms Program
GATE	GARP Atlantic Tropical Experiment
GMS	Geostationary Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite
HBL	hurricane boundary layer
HRD	Hurricane Research Division
LPATS	Lightning Position and Tracking System
MDR	manually digitized radar
MMS	Miami Meteorological Society
MRF	medium range forecast
MSL	mean sea level

NCAR	National Center for Atmospheric Research
NESDIS	National Environmental Satellite, Data and Information Service
NHC	National Hurricane Center
NMC	National Meteorological Center
NORDA	Naval Oceanographic Research and Development Authority
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
OAO	Office of Aircraft Operations (now AOC)
ODW	Omega dropwindsonde
PBL	planetary boundary layer
QBO	quasi-biennial oscillation
QSTING	quasi-spectral time integration on nested grids
RAM	relative angular momentum
RSMAS/MPO	Rosenstiel School of Marine and Atmospheric Science/Division of Meteorology and Physical Oceanography (University of Miami, Coral Gables, Florida)
SAFER	spectral application of finite element representation
SFMR	stepped-frequency microwave radiometer
SLOSH	sea, lakes, and overland surges from hurricanes
SMMR	scanning multifrequency microwave radiometer
SSM/I	special sensor microwave/imager
SST	sea-surface temperature
TIROS	Television and Infrared Observation Satellite
TRMM	Tropical Rainfall Measuring Mission
UW	University of Washington
VA	vorticity advection
VAS	VISSR Atmospheric Sounder
VICBAR	barotropic hurricane track prediction model
VISSR	Visible and Infrared Spin-Scan Radiometer
WMO	World Meteorological Organization