DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

HURRICANE RESEARCH DIVISION

FISCAL YEAR 1990 PROGRAMS - FISCAL YEAR 1991 PROJECTIONS

Staff, Hurricane Research Division

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

January 1991

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

HURRICANE RESEARCH DIVISION

FISCAL YEAR 1990 PROGRAMS - FISCAL YEAR 1991 PROJECTIONS

Staff, Hurricane Research Division

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida
January 1991

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

CONTENTS

Page

Page

OVERVIEW

HURRICANE RESEARCH DIVISION

ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORY

FY-90 PROGRAMS - FY-91 PROJECTIONS

INTRODUCTION

The Hurricane Research Division (HRD) is NOAA's primary focus for research on hurricanes and tropical meteorology. HRD's research is directed at improved hurricane prediction through improved physical understanding of the structure and dynamics of these storms. HRD uses 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.

Some highlights of the FY-90 hurricane field program follow. HRD conducted research flights in Hurricane Jerry over the Gulf of Mexico in October 1989. A single-aircraft version of the synoptic-flow experiment was carried out on 14 October. During this flight, 22 Omega dropwindsondes (ODW's) were dropped and airborne Doppler radar data were collected near the center of the tropical storm. At this time the storm had a minimum central pressure of 994 mb and maximum flight-level winds of 25 m s^{-1}. The flight track provided ODW coverage for most of the Gulf of Mexico north of 22.5°N. Jerry moved north, then west, then north again, and went inland in eastern Texas as a minimal hurricane. Using the ODW data, HRD's experimental barotropic model (VICBAR) made a very good 36 to 48 h forecast of Jerry's complicated track. The second research flight into Jerry was a long-term monitoring pattern at 1,500 m later on the same day. The aircraft recorded excellent flight-level and radar data. Two ODW's were dropped in the eye. These data will be useful in the study of the core structure of a tropical storm that is under the influence of strong, upper level shearing winds.

HRD conducted research flights in Hurricane Gustav from 27 to 31 August 1990. On 27 August, one of the WP-3D flew a rotating figure-4 pattern with radial legs of 150 km at 1,500 m as part of a vortex dynamics experiment. During this flight, Gustav had a minimum sea-level pressure of 966 mb and maximum flight-level winds of 45 m s^{-1}.

A two-aircraft eyewall evolution experiment was conducted on the following day when Gustav had a minimum sea-level pressure of 978 mb and maximum winds of 45 m s^{-1}. This experiment was repeated on 29 August. On 30 August, both aircraft were restaged from San Juan to Bermuda and conducted a shortened version of the eyewall evolution experiment en route to Bermuda. Upon arrival at Gustav's center, the aircraft found a deepening storm with a minimum surface pressure of 958 mb and maximum winds of 55 m s^{-1}.

The eyewall evolution experiments obtained complete mappings of the three-dimensional wind field with the airborne Doppler radar while the aircraft were in Gustav's core. One of the WP-3D's monitored the hurricane at 1,500 m and the second aircraft flew at 3,000 m. The air crews coordinated the eyewall penetrations so that the flight tracks were at right angles to each other and the aircraft crossed the center of the eye <1 to 2 min apart. During the downwind legs outside of the eyewall, Doppler data were recorded using the FAST (forward and aft scanning technique). As a result of the scanning strategy, HRD collected observations at all locations with scatterers within 100 km of the center of the eye and at intervals of 35 to 40 min. The repeated mappings of the wind field will allow studies of the temporal evolution of the vortex and possibly lead to insights into the mechanisms responsible for intensity change.

On 31 August, HRD completed a two-aircraft energetics experiment in Hurricane Gustav. One of the aircraft recorded Doppler and flight-level observations in Gustav's core while the other WP-3D released ODW's from the highest attainable altitude in an annulus 300 to 450 km around the moving storm center. Analyses of these observations will help to determine the energy sources, transports, and energy conversions that are pivotal to understanding and forecasting intensity changes of tropical cyclones.

Tropical Depression 11 (TD11) formed in the central tropical Atlantic on 18 September from an easterly wave of African origin. HRD conducted single-aircraft investigations of the structure of TD11 during the daylight hours from 19 to 21 September. Each year, about 50 easterly waves pass through the Atlantic tradewind belt. Five or six of the waves become tropical storms or hurricanes and another two or three, called depressions, develop closed cyclonic circulations, but their maximum winds remain less than tropical storm strength. The question of why so few easterly waves develop into tropical storms is unanswered. TD11 is an example of the nondeveloping majority.

On 27 and 28 September 1990, ocean cumulus experiments were conducted over the eastern Bahamas to document the dynamics, microphysics, and electrification of isolated tropical convective cells at stages of their life cycles. Upward- and downward-looking electric field mills were tested. These instruments provide a broad-scale perspective of atmospheric electrification. Also tested was the Q-probe, which determines electric charges on individual cloud particles. On 27 September, a single-aircraft cumulus experiment was flown and, on the following day, a two-aircraft experiment was conducted in about the same location.

The single-aircraft experiment combined cloud penetrations, which obtained in-situ measurements of vertical velocities and microphysical particles, and circumnavigations of the clouds, which provided airborne Doppler radar of the cloud wind field. In the two-aircraft experiment, one aircraft sampled the clouds at altitudes ranging from 3 to 7 km, while the lower level aircraft concentrated on FAST mapping of the clouds and low-level penetrations near cloud base. The WP-3D's sampled clouds with predominately warm rain processes and clouds with both warm rain and ice processes. The electrification instruments appeared to operate as designed and the data set should provide a significant contribution to the objectives of the experiment.

Single-aircraft missions on 29 and 30 September were conducted in a tropical cloud cluster south of the western tip of Cuba. The cloud-cluster flights tested the patterns proposed for a tropical cyclogenesis experiment that is tentatively being planned for the Acapulco area in July 1991 in collaboration with Massachusetts Institute of Technology (MIT) scientists. The flight pattern was flown successfully on both days. HRD scientists will evaluate the flight patterns and discuss possible improvements with MIT scientists.

HURRICANE RESEARCH DIVISION PERSONNEL

Composition of Full-Time Staff - FY-90

Degree	HRD Personnel
Ph.D.	12
M.S.	11
B.S.	9
B.A.	1
Paraprofessional	5

UNIVERSITY RELATIONS

Cooperative Research[1]

Organization	Research/Cooperative Investigator
Desert Research Institute, University of Nevada System	Electrification and Precipitation Processes in Tropical Convection - Dr. John Hallett
National Center for Atmospheric Research	Hurricane Rainbands: Mesoscale and Convective-Scale Structure - Dr. Gary M. Barnes - Dr. Margaret A. LeMone
State University of New York at Albany	Intensity Changes in Hurricane Allen - Dr. John Molinari
State University of New York at Albany	Analysis of a Secondary Eyewall Event - Dr. John Molinari
University of Massachusetts	Microwave Remote Sensing of Hurricanes - Dr. Calvin T. Swift
Meteorology and Physical Oceanography Department/University of Miami	Small Doppler Radars as Precipitation Gage for TRMM Ground Truth - Dr. Roger Lhermitte
University of Oklahoma	Analysis of the Landfall of Hurricane Gilbert (1988) - Dr. Howard B. Bluestein
University of Washington	Analysis of AOML/HRD P-3 Doppler Radar Data - Dr. Robert A. Houze, Jr.

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

University-Associated Speakers at HRD

1989

November 16	University of California at Irvine Dr. Carl Friehe: "Surface-Layer Turbulence Around a Sea Surface Temperature Front: Measurements From Two Turbulence Aircraft"

1990

January 29	Massachusetts Institute of Technology Dr. Kerry Emanuel: "Negative Influences on Axisymmetric Tropical Cyclogenesis"
February 12	University of Washington Dr. Robert A. Houze, Jr.: "The Equatorial Mesoscale Experiment (EMEX): An Overview and Prelimiary Results"
February 13	University of Massachusetts Dr. Calvin T. Swift: "Design and Performance of an Airborne C-Band Scatterometer to Measure the Ocean Surface Wind Vector"
February 21	McGill University Dr. John R. Gyakum: "A Diagnostic Study of Cyclogenesis in the Western North Pacific Ocean"
February 22	McGill University Dr. John R. Gyakum: "Antecedent Meteorological Conditioning Associated With Explosive Surface Cyclogenesis"
March 7	Massachusetts Institute of Technology Mr. Mark D. Handel: "Tropical Cyclone Intensification From Finite Amplitude Disturbances"
March 9	Massachusetts Institute of Technology Mr. Mark D. Handel: "Greenhouse Science History From Explanation to Prediction"
July 16	State University of New York at Albany Dr. John Molinari: "Environmental Interactions and Hurricane Intensity Change"
August 1	North Carolina State University Dr. Jong-Jin Baik: "Intense Mesoscale Vortices Developed and Maintained by Vortex-Ocean Interaction"

Adjunct Faculty Members (1990-1991)

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

Ph.D. Committee Memberships

Committee Member:	Dr. Mark DeMaria
Degree Candidates:	Mr. Kiran Alapatti Mr. Jainn-Jong Shi
Affiliation:	Department of Marine, Earth and Atmospheric Sciences North Carolina State University
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-90 PROGRAMS - FY-91 PROJECTIONS

LABORATORY RESEARCH

1. Observational Hurricane Studies

1.1 The Synoptic-Scale Environmental Flow Around Mature Hurricanes

Goals

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 required data. The ODW's measure temperature, relative humidity, and pressure from flight level to the sea surface. 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.

During these experiments, 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. At NMC they are used in the analyses that initialize dynamical hurricane track models. An important goal of the project is to assess whether the ODW observations help to improve the official hurricane track forecasts issued by the NHC. A second major goal is to determine the impact of the ODW data on the NMC's operational objective analyses and dynamical hurricane track model.

Accomplishments (FY-90)

HRD scientists are using 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 in section 6. That project is also evaluating VAS [VISSR (Visible and Infrared Spin-Scan Radiometer) Atmospheric Sounder] data over the tropical Atlantic based upon comparisons with the ODW observations.

Postprocessing of ODW data was completed for all sondes dropped during 1989 HRD Hurricane Field Program flights. These flights included synoptic-flow experiments in Hurricanes Hugo and Jerry, and hurricane energetics and budget experiments in Hurricanes Dean, Gabrielle, and Hugo. A total of 178 ODW's was processed. ODW data from the synoptic-flow experiments were distributed to interested researchers.

Software was developed for the HP-UNIX airborne workstation for real-time processing of ODW data. The software receives ODW data from the WP-3D NOVA ODW computer, allows the user to display, manipulate, and edit the sounding, and encodes mandatory- and significant-level wind and thermodynamic reports into the WMO (World Meteorological Organization) TEMP DROP message format. The formatted message can then be relayed digitally to the WP-3D ASDL (aircraft-satellite data link) computer for transmission to NHC and NMC. Before the development of this software, only mandatory-level ODW data were transmitted from the WP-3D's. Researchers at NMC feel that the operational analysis system will respond better to the significant-level ODW observations.

Plans (FY-91)

ODW data from the 1990 HRD Hurricane Field Program will be postprocessed. Data from synoptic-flow experiments will be distributed to interested researchers.

Software for real-time processing of ODW data on the HP-UNIX airborne workstation will be modified in response to experience gained in 1990 during the hurricane field program.

NMC will complete analyses and forecasts for one or two cases with ODW observations. A global spectral forecast model with a resolution of at least T120 will be used.

1.2 Mesoscale Precipitation Features in Mature Hurricanes

Goals

The goals of this work are the identification of mesoscale convective features in mature hurricanes through the use of airborne radar and a description of their basic organization and structure. In progress are studies of the differences in wind, radar reflectivity, and vertical velocity fields between the convective precipitation regions in the eyewall and the nonconvective precipitation regions surrounding the eyewall.

Accomplishments (FY-90)

Two of three manuscripts describing an analysis of the eyewall water budget study in Hurricane Norbert on 24 to 25 September 1984 have been completed and submitted for publication. These manuscripts, respectively, concentrate on the kinematic structure of the eyewall, and on the microphysical and radar structure. A third manuscript that describes the techniques used to derive the water budget is nearing completion. This report will include a description of our implementation of algorithms to retrieve thermodynamic variables from the Doppler wind analysis.

Airborne Doppler radar data are being used with other data, including those from ODW's, in the objective analysis of the Hurricane Gloria (1985) wind field. The analysis, which can depict the inner core wind structure, matches the ODW data at the edges of the analysis domain. The sharp wind shear region along the eyewall is clearly defined in the analysis. These kinematic fields will be useful for the study of interactions of the inner core circulation with its environment. We have begun Doppler radar analyses for similar data sets in Hurricanes Emily (1987) and Florence (1988).

In cooperation with NCAR, real-time airborne Doppler wind algorithms were devised to compute the radius-height mean tangential wind field and a measure of the asymmetric structure of the wind field from one flight leg through the storm. The algorithm has proven to be excellent at resolving the radius-height structure of the tangential and radial wind, as well as the wave number one azimuthal variation of the tangential wind.

Analysis of the now famous WP-3D flight into Hurricane Hugo on 15 September 1989 continues. A detailed analysis of the flight-level and radar data has been completed. The bulk of the severe turbulence encountered was related to the aircraft's penetration of an intense vortex, which was on the scale of 2 to 3 km and embedded along the inside edge of the eyewall. The vortex was positioned at a radius of 7 km from the geometric center of the radar eye, between the inside portion of the radar eyewall and the cloud boundary. It was characterized by a peak tangential flow of 25 to 30 m s^{-1} and a radius of 1.0 to 1.5 km, a central pressure perturbation of 10 to 11 mb collocated with a 10 m s^{-1} downdraft, and intense updrafts at the radius of the maximum tangential wind. The vorticity associated with the vortex was 0.1 s^{-1}, about a factor of 6 larger than the background eyewall vorticity.

The vortex was tracked as it rotated around the eye along the inside edge of the eyewall. There were distinctly separate wind and pressure perturbation centers at different radii from the geometric center of the radar eye. Three complete circuits of the pressure and wind centers, at ~19 min each, were mapped. The pressure center, at a radius of ~7 km, had a translation velocity of 35 m s^{-1}, and the wind center, at a radius of ~4 km, had a translation velocity of 20 m s^{-1}. The storm was also moving toward the northwest at ~7.5 m s^{-1}. The pressure center was clearly associated with the vortex. The migrating wind center appeared to be a perturbation about the eyewall circulation center. The vortex appeared to weaken with increasing altitude.

Plans (FY-91)

We are studying the differences in the wind, radar reflectivity, and vertical velocity fields between the convective precipitation regions in the eyewall and the nonconvective precipitation region surrounding the eyewall. Data are from Hurricanes Norbert, Elena (1985), Gloria, Emily, Gilbert (1988), and Hugo. Analyses of the relationships among the changes in organization and structure of the precipitation features and changes in storm wind field and track are also under way. Data from Hurricanes Norbert, Elena, Gloria, Gilbert, and Hugo are being used for these studies.

The analysis of the Hurricane Emily water budget will be completed.

The 15 September Hurricane Hugo analysis will be completed. Photogrammetric analysis of the side camera film will be attempted so as to relate the eyewall cloud features to the vortex observed in the flight-level data and on a Doppler radar analysis of portions of the eyewall.

Work to incorporate airborne Doppler wind data and ODW data into the Ooyama-Lord HRD objective analysis scheme for Hurricanes Gloria (24 and 25 September 1985), Emily (23 and 24 September 1987), and Florence (8 September 1988) will continue.

Development and testing of real-time airborne Doppler wind analysis algorithms in collaboration with NCAR will continue.

1.3 Convective Rainbands in Hurricanes

Goals

In cooperation with NCAR, we are assessing the role of hurricane rainbands in the modification of hurricane structure and intensity. Interest is focused on the thermodynamic recovery of the hurricane boundary layer (HBL) after it has been modified by rainband downdrafts and the way that this modification affects the eyewall convection. The vertical transport of angular momentum within rainbands and its effect on the angular momentum of the inflow air are also important. The structure and dynamics of the HBL in the vicinity of rainbands are being compared with the results of recent investigations of eyewall convection and tropical squall lines, and to nontropical, synoptically forced rainbands.

Accomplishments (FY-90)

Analysis of data obtained in a rainband/boundary layer experiment flown in Hurricane Gilbert on 12 September 1988 while the center was making landfall over Jamaica is in progress. Radar data indicate that a succession of convectively active rainbands formed in a region ~150 km to the southeast of the storm center. Aircraft data suggest that a storm-stationary convergence line was responsible for initiation of the bands. Aircraft and ODW soundings indicate that the boundary layer was disturbed on the outer side of the band beneath strong subsidence areas within stratiform rainfall.

NCAR scientists have completed analyses of the flight-level data for six flights into Tropical Storm Isabel (8 to 10 October 1985). Preliminary results, presented at the American Meteorological Society (AMS) *4th Conference on Mesoscale Processes* (June 1990, Boulder, Colorado) indicate that a secondary storm center developed beneath a "supercell" convective complex located 60 km north of the original center and became dominant with an associated tangential wind maximum. The circulation associated with this new center was insufficient to maintain convection long enough for the tropical storm to develop into a hurricane. Competition between the two centers for the inflow air may have disrupted the development of the warm core. A paper describing these results was submitted to the *Monthly Weather Review*.

Work continued on a study of a Genesis of Atlantic Lows Experiment (GALE) rainband. Dry static energy cross sections, constructed from ODW's, indicate warm frontal lifting of $\sim$20 cm s^{-1} as the inflow air in the boundary layer approached the band. Two ODW soundings in the vicinity of the active convection showed evidence of downdraft transport of cooler drier air from midlevels into the boundary layer. Preliminary results were presented at the AMS *4th Conference on Mesoscale Processes*.

Plans (FY-91)

Priority will be given to further study of the Hurricane Gilbert rainband data experiment and to completion of the studies of the GALE rainband.

1.4 Vortex Motion and Dynamics

Goal

The goal of this research is improved forecasting of hurricane motion and intensity through better understanding of hurricane dynamics. To achieve this goal, relatively simple, quasi-analytical, theoretical models are formulated and studied, aircraft observations are analyzed and studied in the post-season mode, and real-time analyses of aircraft data to support NHC forecasts are carried out.

Accomplishments (FY-90)

Work has started on a nonlinear, shallow-water, semispectral vortex motion model. The left-hand sides of the governing equations are the linear equations for the wave number 1-3 asymmetries; the right-hand sides contain the nonlinear interactions and forcing that arises from environmental currents, convection, and the beta effect. Preliminary calculations indicate that, without nonlinear interactions, the model has the same normal mode at zero frequency and unphysically fast poleward motion that occurred in a linear steady-state model studied previously. (A paper describing the linear model's normal modes was published in the September 1990 issue of the *Journal of the Atmospheric Sciences*.) Further calculations with the fully nonlinear model should demonstrate how nonlinearity reduces this unrealistic normal-mode response.

During the 1989 hurricane season, flight-level observations in Hurricanes Dean, Gabrielle, Hugo, and Jerry were collected. The HRD random access data base now contains 1,056 radial profiles in 24 Atlantic hurricanes and tropical storms plus 74 profiles in eastern Pacific Hurricane Norbert (1984).

Studies of the Hurricane Hugo data set indicate that the storm apparently experienced three eyewall replacements. The first occurred as Hugo approached the Lesser Antilles. The second took place when environmental shear inhibited intensification in the open Atlantic, and the third occurred as Hugo approached the Carolina coast. The first two replacements conform with observations in previous hurricanes. Here, the hurricane weakened as the eye discontinuously expanded. The last eyewall replacement was different. The hurricane strengthened as the eye expanded and continued to strengthen afterward. However, before the replacement, the hurricane had weakened to 38 m s^{-1} maximum flight-level wind. Observations at the start of the concentric eye episode show that the wind profile was flat and that the outer wind maximum was as strong as the inner. Thus, no reduction of maximum wind occurred as the inner eyewall weakened, because the outer eyewall was already stronger than the inner.

Two papers describing the development of the tangential wind in hurricanes and its balance with the pressure field appeared in the 15 January 1990 issue of the *Journal of the Atmospheric Sciences*. A note refining the estimate of the Hurricane Gilbert (1988) record minimum sea-level pressure appeared in the December 1989 *Monthly Weather Review*.

The software for real-time analysis of aircraft observations now ingests observations transmitted from both NOAA and USAF aircraft, constructs objective storm tracks, and prepares depictions of the hurricane's structure in storm-centered coordinates. We have adapted the storm-centered analysis algorithm (SCAAL) package to real-time use and have prepared analyses and interpolated fields based upon data transmitted in real time.

The track-fitting part of the real-time package shows promise for improved initialization of objective forecast aids. It uses cubic splines to approximate the storm track parametrically, and it is possible to control the smoothness of the fitted track by adjusting the number of nodes. Experimentation with initialization of the climatology/persistence model (CLIPER) with spline tracks shows that this technique works best with 1 degree of freedom (one additional node) for each 12 h of storm history. Although splines initialization is competitive with the subjective tracks determined in real time by NHC, no single value of smoothing allows it to outperform the subjective operational track consistently.

A second means of real-time track fitting involves variational manipulation of the track to minimize the apparent asymmetry caused by misplacement of the center of rotation. The algorithm searches the six-dimensional hyperspace defined by the vortex center's mean position, motion, and acceleration to minimize the kinetic energy of the vector difference between the total wind and the cyclonically circulating wind summed over the observations. In a preliminary test, the variational technique does about as well as fitting a smooth track to the entire storm history.

Plans (FY-91)

The shallow-water nonlinear vortex motion model should be completed and tested. This model should provide new insight into the physics of vortex motion. Experimental runs and interpretation of the results will require most of FY-91.

Collection of flight-level data will continue in FY-91 to support real-time analysis and broaden experience with hurricane evolution. In FY-91 we plan to fly weak systems in the Atlantic and eastern Pacific in a cooperative investigation with Massachusetts Institute of Technology scientists. These flights will focus on midlevel moistening and inhibition of intensification by cool, evaporatively driven, convective downdrafts.

A manuscript describing the history of Hugo's three eyewall replacements and environmental interactions will be completed and submitted for publication.

The forecast errors that arise when CLIPER is initialized with spline tracks using various amounts of smoothing will be studied in the hope of finding stratifications or rules of thumb for selection of optimum smoothing in particular situations. Studies of the variational track determination will continue and the evaluation of spline-based tracks will be completed.

1.5 Microphysical Studies in Hurricanes

Goals

A primary 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. The emphasis is 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. We will also compare the microphysical characteristics and overall importance of convectively active regions of the storm with the more stratiform regions.

Accomplishments (FY-90)

"Radar Reflectivity-Ice Water Content Relationships for Use Above the Melting Level in Hurricanes" was published in the September 1990 issue of the *Journal of Applied Meteorology*. This work describs 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 both 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.

The final analysis of the microphysical data from Hurricane Emily on 22 September 1987 was completed. Most of the eyewall data were obtained at temperatures >0°C. The peak cloud liquid water observed with the Johnson-Williams (JW) device was ~2.3 g m^{-3}. Similar JW liquid water contents were observed in the eyewalls of Allen (1980) and Irene. As has been noted in other hurricanes, downdrafts in Emily usually contained ice crystals in concentrations >100 per liter, and the only identifiable ice crystal types were columns and graupel.

The electric field data collected in previous seasons has been analyzed. The strongest eyewall electrical activity occurred in or near updrafts >12 m s^{-1} in eyewalls with diameters greater than ~25 km. Hurricanes with larger diameter eyewalls had weaker updrafts and correspondingly less electrical activity. These results were presented at the AMS *Conference on Cloud Physics*, July 1990, San Francisco, California, and published in the conference preprints.

The paper "Dual-Aircraft Investigation of the Inner Core of Hurricane Norbert: Part II, Mesoscale Distribution of Ice Particles" was submitted to the *Journal of the Atmospheric Sciences* in July 1990. This paper describes the spatial distribution of hydrometeors in Hurricane Norbert and compares it with the radar reflectivity. Airborne Doppler winds were used to compute typical ice particle trajectories. It was found that the large graupel remained in the eyewall instead of being advected radially out, but the smaller ice particles were advected out of the top and sides of the eyewall. Some of these particles grew by aggregation and diffusion and fell out to form a rainband. The region between the eyewall and the rainband was dominated by small ice particles in concentrations at 6 km that were advected out of the eyewall, but did not grow.

A paper on hurricane microphysical trajectories, jointly prepared with an NCAR scientist, was presented at the AMS *Conference on Cloud Physics* and published in the preprint volume.

A report based upon HRD's 1989 Oceanic Cumulus Experiment, written jointly with a DRI scientist, was presented at the AMS *Conference on Cloud Physics* and appears in the preprint volume. A second joint paper with a DRI scientist, on oceanic convective clouds, has been accepted by the *Journal of the Atmospheric Sciences* and tentatively scheduled for December publication.

Work is continuing on the adaptation of an NCAR microphysical trajectory model to hurricane data. Numerous model runs have been made on Hurricane Emily.

Plans (FY-91)

In cooperation with NCAR scientists, trajectories of ice from the eyewall, and from other convective features of hurricane rainbands, will be the subject of continued study. The analysis of the oceanic cumulus data will continue.

The analysis of stratiform regions in hurricanes, particularly Hurricane Newton (1986), will be continued and expanded.

Work will be continued 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. We will investigate whether stratiform precipitation areas and hurricane development are related to the development and changes in the major convective features of storms.

Electric field and particle charge data gathered during the 1990 hurricane season will be analyzed to determine the mechanisms by which hurricane convection is electrified. We will attempt to determine the conditions under which the eyewall convection becomes charged and to identify the particles that carry a charge. The amount of electrification will be correlated with the size and strength of the eyewall updrafts.

1.6 Convective-Scale and Mesoscale Structure of Hurricanes Over the Open Ocean or During Landfall

Goal

The goal of this project is the analysis and interpretation of digital radar data that are recorded at National Weather Service (NWS) offices during the landfall of hurricanes and by the NOAA WP-3D research aircraft over the open ocean. The emphasis of the analyses is on the description of important changes in the convective-scale and mesoscale patterns of precipitation over the open ocean and during landfall. Vertical motions in the core of hurricanes using radial velocities at vertical incidence from the airborne Doppler radars are also being studied.

Accomplishments (FY-90)

Calculations of hurricane-core vertical motions from vertical incidence Doppler radar data were completed for three flights in Hurricane Elena (1985) and one flight in Hurricane Emily (1987). Preliminary computations indicate that the mean upward motion was ~ 0.5 m s^{-1} throughout the troposphere. The largest upward vertical velocities (5 to 25 m s^{-1}) occurred near the inner edge of the eyewall and typically increased in strength from the lower to upper troposphere. Updraft cores tended to be larger than downdraft cores. In Hurricane Emily, an intense storm with a small eye, vertical motions in the eyewall were stronger, the updraft cores were smaller, and the updrafts were more vertically aligned than in Hurricane Elena.

Radar composites and flight-level analyses were completed for a study of Hurricane Gilbert's (1988) concentric eyewall cycle. An outer eyewall contracted and Gilbert weakened before the hurricane struck Cozumel, Mexico, and the coast of the Yucatan peninsula. Satellite images provided indications that the outer eyewall continued to contract as Gilbert crossed the Yucatan. When Gilbert emerged over the Gulf of Mexico, the inner eyewall was a weak fragment near the storm center and the outer eyewall had become dominant. This case provided the first evidence that the concentric eyewall cycle can continue for at least a few hours as a hurricane crosses flat land. A manuscript describing Gilbert's concentric eyewall cycle is in preparation.

Airborne Doppler wind data were obtained from the eyewall region of Hurricane Gilbert during a research flight following the measurement of the record low (Atlantic basin) sea-level pressure of 888 mb. Two Doppler boxes were flown in Gilbert's core when the minimum surface pressure was ~891 mb. Maximum flight-level winds were 70 m s^{-1} at 700 mb. The analysis domain included the inner eyewall and part of the precipitation-free moat surrounding the eyewall. Gilbert's minimum sea-level pressure was considerably lower than the sea-level pressure in Hurricanes Norbert (1984), Gloria (1985), and Emily, for which similar analyses exist. In Gilbert, the inner eyewall was more circular, and the precipitation-free moat region was better developed.

Analyses of surface data were completed for Tropical Depression 2 of 1987. The analyses identified areas where surface wind speeds exceeded tropical storm strength. Several hours before landfall, two areas of strong convection 200-400 km east of the center of the depression produced mesoscale downdrafts that cooled the surface air temperature by 5° to 6°C and increased the surface wind speeds. A squall line formed in southwestern Louisiana ~6 h before landfall and caused strong surface winds that persisted over the northern Gulf of Mexico until 9 h after the center of the depression crossed the coast. As a result of the convective activity, lapse rates over the warm surface of the Gulf of Mexico were unstable and estimates of wind speeds at 10 m were nearly the same as those measured by reconnaissance at altitudes from 150 to 200 m. Diagnostic calculations are in progress to estimate the role of surface heat fluxes in modifying the thermal structure of the boundary layer. A manuscript is in preparation.

Land-based radar teams at Lake Charles, Louisiana, and Galveston, Texas, recorded data during the landfall of Hurricane Jerry (1989). Data collected during the landfall of Hurricane Hugo (1989) were processed.

Plans (FY-91)

Calculation of the vertical motions measured by the airborne Doppler radars in Hurricanes Diana (1984), Gloria, Gilbert, Joan (1988), Dean (1989), Gabrielle (1989), Hugo, and Jerry will be completed. This will bring the total sample size to ~150 radial legs. We intend to stratify the sample by eyewall, rainband, and stratiform areas and to display the distribution of vertical velocity and the size of updrafts and downdrafts as a function of altitude.

Manuscripts on the concentric eyewall cycle in Hurricane Gilbert and Tropical Depression 2 of 1987 will be submitted for publication.

The three-dimensional wind analysis of the core of Hurricane Gilbert will be completed. We will compare the eyewall structure with previously published studies of Hurricanes Alicia (1983) and Norbert and studies of Hurricanes Gloria and Emily that are in progress.

1.7a Hurricane Planetary Boundary Layer

Goals

Relationships between flight-level winds at various altitudes and surface winds over the ocean in hurricane situations will be developed to allow hurricane forecasters to deduce surface winds from aircraft data. An objective analysis scheme will be developed to analyze surface wind data obtained from ships of opportunity, buoys, platforms, coastal automated stations, coastal and inland hourly and synoptic reporting stations, and adjusted aircraft data to provide real-time surface wind charts in the vicinity of hurricanes.

The transition of the hurricane boundary layer from its open ocean state to a condition of decay after landfall will be documented, and a conceptual model of the response of a hurricane to the forcing brought on by the landfall process will be developed.

Accomplishments (FY-90)

A data base of aircraft-buoy wind comparisons was expanded to include data through the 1989 hurricane season. An additional data base was created containing comparisons of maximum visually estimated surface winds and maximum measured flight-level winds based upon vortex message reports collected from 1975 to the present. The relationship between aircraft and buoy-measured winds is strongly dependent upon stability and less clearly dependent upon altitude. A larger scatter was shown for the 700-mb flight level, but, in general, for unstable conditions, surface winds are 76% of flight-level winds and for stable conditions, surface winds are 54% of flight-level winds. Gust factors are highly dependent upon the averaging period of the observation platform. The larger the averaging period, the higher the gust factor. A paper summarizing these results was presented at the Florida State University Department of Meteorology *40th Anniversary Symposium*.

The surface wind analysis package was employed in a research mode to document the surface wind distribution of Hurricane Hugo (1989). These analyses were made available to the storm surge modeling community of NOAA and the Army Corps of Engineers. The results show that the hurricane's northwestward motion was influenced by synoptic flow associated with the mid-Atlantic ridge and a cutoff low near the Florida panhandle. In the hours preceding and subsequent to landfall, an approaching midlatitude trough and strengthening ridge contributed to Hugo's acceleration. Rapid intensification of 1 mb h^{-1} occurred over a 6 h period before landfall and appeared to be associated with both low upper level wind shear on the storm periphery and passage of Hugo over the Gulf Stream.

Based upon objective analyses of the surface observations and adjusted aircraft winds using the Ooyama-Lord technique, Hugo's maximum sustained surface winds at landfall were confined to a small crescent-shaped region in the north-to-northeast portion of the eyewall. These winds reached 54 m s^{-1} in the coastal area of Bulls Bay in South Carolina, with gusts to 65 m s^{-1}. Adjacent to the coastline, winds decreased considerably because of frictional effects within 1 to 5 km of the coast. Wind profiles derived from airborne Doppler radar over water and radiosonde observations over land indicate that the level of maximum wind speed was between .5 and 2 km and that wind shear over land was very strong.

Hugo's maximum sustained surface winds decreased to just below hurricane force (30 m s^{-1}) in the vicinity of Columbia and Sumter in South Carolina, with peak gusts of 49 m s^{-1}. Hugo reached the Charlotte, North Carolina, area with tropical storm-force winds (24 m s^{-1}) and gusts to 39 m s^{-1} 6 h after landfall. Despite the decay of Hugo's mean circulation, surface gust speeds were 50% greater than the sustained speeds in most portions of the storm and up to 100% greater in the northeast portion of the eyewall. These gusts contributed to much of the inland damage.

A manuscript entitled "The Landfall of Hurricane Hugo in the Carolinas" has been accepted by *Weather and Forecasting*. Results were presented at: a Congressional briefing to the U.S. Senate Commerce Committee in Washington in November; the "Special Session on Hurricane Hugo" of the *70th Annual Meeting of the American Meteorological Society* in Anaheim, California, in February; a conference on Hugo sponsored by the National Science Foundation at the University of Puerto Rico at Mayaguez in March, and a workshop on Hurricane Hugo sponsored by the American Shore and Beach Preservation Association at Folly Beach, South Carolina, in May.

Plans (FY-91)

We will complete, and submit to the *Monthly Weather Review*, a manuscript entitled "Estimating Oceanic Surface Winds in Hurricanes: Relationships Between Aircraft Reconnaissance and Oceanic Platforms." This paper describes the results of comparisons between NOAA aircraft and buoy wind observations that were gathered over the past 10 years.

If a major hurricane strikes the U.S. coast, the objective surface-wind analysis package described above will be implemented in a research mode, as was done with Hugo.

Completion of an additional Loran station in the southwest United States will provide improved vertical soundings. We will use the NSSL mobile CLASS (Cross-Chain Loran-C Atmospheric Sounding System) launch facilities during hurricane landfalls that occur on the the Gulf of Mexico coast.

1.7b Hurricane and Tropical Air-Sea Boundary Layer Processes

Goals

The goals of this project are the simultaneous study of the structure and dynamics of the atmospheric and oceanic boundary layers in tropical cyclones and a study of the role of air-sea fluxes in the evolution of hurricanes and other marine tropical weather systems.

Accomplishments (FY-90)

Analysis continues of the data from the joint NOAA/Navy air-sea interaction experiment that was conducted in the Gulf of Mexico from NOAA hurricane research aircraft before, during, and after the passage of Hurricane Gilbert (1988) through the Gulf.

Studies are in progress to describe the evolution of the sea surface fluxes of latent and sensible heat along a trajectory passing over three sea surface temperature (SST) distributions. The initial points were on the inner edge of principal rainbands located east, south, and west of the center of a mythical hurricane. The properties of the initial parcels were assumed to be that of cool, dry, downdraft air from a band similar to one observed in Hurricane Earl (1986). Trajectories into the eyewall were calculated using the vortex wind field and the SST cooling pattern from Hurricane Earl. The rate of recovery of the planetary boundary layer depth and the equivalent potential temperature were calculated using a GATE [GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment] boundary layer model that was adapted for hurricanes. A new parameterization for the drag coefficient was used that deviates considerably from conventional wind-speed-dependent formulations. The new relationship depends upon significant wave height and fetch (radius from the storm), which are estimated from a parametric model. The results showed that the rate of recovery of the downdraft air depends rather strongly upon the SST along the trajectory. When the trajectory passes over the cold wake left by the storm, little recovery occurs. The effect of a downdraft perturbation on the eyewall region, therefore, depends upon the quadrant of the storm from which the downdraft emanates.

Work on the determination of surface winds using the Stepped-Frequency Microwave Radiometer (SFMR) mounted on the WP-3D aircraft has continued. A new, on-board algorithm for real-time surface wind determination has been installed on the WP-3D and will be undergoing further check-out during the 1990 hurricane season.

Work has continued on the analysis of SFMR data from previous years. Data from Earl, Florence (1988), Gilbert, Dean (1989) and Hugo (1989) indicate that the mean surface winds can be estimated by the SFMR to within 1.5 m s^{-1} when the winds are between 15 and 60 m s^{-1}. The emissivity measured by the SFMR is a linear function of surface stress as calculated by the HRD boundary layer model. Therefore, the SFMR can also measure surface stress.

Analysis of surface wind speeds obtained from the airborne SFMR shows that the radius of maximum wind at the surface is typically 30% smaller than at flight level (500 or 1500 m) and that a distinctly different pattern of asymmetries exists at the surface than at flight level. Preliminary analysis of SFMR data from Emily (1987) and Floyd (1987) shows surface centers were displaced nearly 40 and 100 km, respectively, from the flight-level center at 500 mb.

In collaboration with NHC, an evaluation of the Special Sensor Microwave/Imager (SSM/I) on a DMSP (Defense Meteorological Satellite Program) satellite continues so that we can determine the usefulness of the SSM/I for measuring surface winds in and around hurricanes. The device seems to be of some value for the estimation of surface winds in developing systems, especially near the tropical cyclone threshold of 17 m s^{-1}.

Consultations have continued with AOML's Ocean Acoustics Division about use of the WOTAN (Weather Observation Through Ambient Noise) instrument for measuring rain rate and wind speed over the ocean. Final calibration corrections were made to data obtained during an experimental deployment of the WOTAN off Carysfort Reef. WSR-57 radar data and data from an automatic weather station were also collected in the vicinity of Carysfort Reef. Preliminary analysis of October 1988 data indicated that rainfall rate could be inferred in passing showers and that a unique slope for ambient sound level versus frequency over a 12-frequency band existed for winds between calm and 12 m s^{-1}.

Plans (FY-91)

An in-depth analysis of the Hurricane Gilbert ocean response experiment will continue. Analysis of GOES (Geostationary Operational Environmental Satellite) enhanced infrared images of Gilbert's wake will be undertaken. Hourly evolution of the wake pattern will be used to infer surface current velocities and to compare them with airborne expendable current probe measurements.

An improved version of the SFMR algorithm will be installed on the WP-3D and real-time transmission to NHC of surface winds via the new ASDL will be started by the end of the 1991 hurricane season. Analysis of SFMR data from 1984-88 will continue.

Two east coast flights during the winter, to overfly NOAA Data Buoy Center buoys and obtain additional in-situ surface wind measurements, are planned for further validation of SFMR surface winds. At least two offshore flow regimes, strongly unstable offshore flow and warm, stable, onshore flow, are needed for the validation.

Work will continue on efforts to evaluate the utility of the WOTAN for measuring surface wind speed and rain rate. It is anticipated that this instrument will be used on air-deployed minidrifting buoys and as a "ground truth" measurement of marine wind and rain for future satellite sensors. The present program is designed to evaluate the concept and the proposed algorithm. The latter is similar to that used for the SFMR.

1.8 Tropical Cyclone Supercell Structure

Goal

The goal of this project is an understanding of the formation, structure (thermal, dynamical, and microphysical), and evolution of large supercells within tropical cyclone circulations. It is known that large convective bursts lasting 12 to 24 h and consisting of several shorter period convective pulses may occur near tropical cyclone maximum wind (eyewall) regions. These events disrupt any trends in storm deepening for a day or two. Following this disruption, rapid deepening sometimes occurs.

Accomplishments (FY-90)

We concentrated on the analysis of intense convection in the eyewall of Hurricane Hugo (1989), the mesoscale circulation (suction vortex) implied from the observations, and the motion of mesoscale circulation around the eyewall during a 1.25 h period.

Fujita (1971) coined the term "suction vortex" for small-scale vortices that are embedded within a tornado and that generate localized, intense, damage swaths, or cycloidal "scratch marks" in damage surveys. On a flight into Hurricane Hugo on 15 September (also, see item 1.2 above), when the storm was ~500 km northeast of Barbados, we unexpectedly encountered 90 m s^{-1} peak winds, a 915-mb minimum pressure, a series of updraft-downdraft couplets, and extreme wind shear. These characteristics suggest that an analogous vortex can exist in the eyewall of a rapidly deepening, intense hurricane such as Hugo was on the 15th. Whereas the tornado and suction vortex scales are ~1,000 and 50 m, respectively, the scales of the hurricane eye and attendant "suction vortex" are 20 and 1 km, respectively.

Approaching the eyewall from the west-southwest at an altitude of 500 m, the aircraft experienced a sudden increase in flight-level wind from ~30 to 87 m s^{-1} in 2 min as the radar reflectivity increased from 37 to 49 dBZ in <1 min. The first of three updraft-downdraft couplets was encountered 25 s before the maximum wind. Vertical velocities were ~6 m s^{-1}. This couplet was followed in 15 s by the second one, which had a 9 m s^{-1} updraft that coincided with the maximum wind and a 10 m s^{-1} downdraft, 4 s later, that coincided with the inner edge of the radar eyewall. The most intense couplet occurred 15 s later within the cloudy, but rain-free, region inward of the radar eyewall. Here a 20 m s^{-1} updraft was sustained for >1 min, followed 4 s later by an 8 m s^{-1} downdraft. An updraft of 12 m s^{-1} ensued 2 s later. The flight-level winds decreased to 60 m s^{-1} at the inner edge of the eyewall. This change was followed by a second increase to 82 m s^{-1} in the last rain-free updraft and a sudden decrease in 6 s to <20 m s^{-1}.

These observations suggest that the aircraft penetrated a small-scale, or suction, vortex along the inner edge of the eyewall. A vortex having diameters of 1 to 2 km was penetrated by the aircraft on nine occasions during subsequent orbits of the eye. Penetrations, at gradually increasing altitude, showed that the vortex's maximum strength and smallest diameter appeared to be at cloud base and broadened with height. The vortex rotated around the center of circulation with a period of 19 min. This was the first time that an aircraft had penetrated such a phenomenon in a hurricane, although vortices of this type are probably more common than had been thought.

Several mechanisms may trigger the formation of the suction vortex phenomenon along the inner edge of a hurricane eyewall. One possibility is the imposing of a vigorous updraft in the region of strong, horizontal wind shear at the edge of the eyewall. Both the tilting and twisting terms in the vorticity equation probably would be large (e.g., Davies-Jones[2]). Another mechanism is the instability of the vortex as a whole. A critical shear may be reached that results in a vortex breakdown into smaller vortices that dissipate the horizontal eyewall shear the way that Kelvin-Helmholtz waves dissipate vertical shear.

Plans (FY-91)

Analysis of the flight-level and Doppler radar data will continue. We will reanalyze the airborne Doppler radar and Particle Measuring Systems data for the supercells of Norbert and Diana (1984). We will also attempt to construct a qualitative model of the thermodynamic, kinematic, and microphysical structure of a supercell. Analyses of the satellite images and surrounding environmental flow data will be continued for these cases.

We will begin a climatology of tropical cyclone supercell events that have occurred in the Pacific and Atlantic over the past 10 years.

1.9 Doppler Retrievals in Hurricanes

Goal

Retrievals of pressure, temperature, water vapor, and cloud water content may be obtained from an airborne Doppler wind analysis in a hurricane. This source permits a more continuous analysis of these variables than is possible from flight-level data alone. Among other benefits, such information allows the computation of detailed energy and momentum budgets. The goal of this research is accurate three-dimensional depictions of hurricane the thermodynamic and microphysical structure and evolution.

Accomplishments (FY-90)

Dr. Frank Roux of the Centre de Recherches en Physique de l'Environment Terrestre et Planetaire, in Issy-Les-Moulineaux, France, began a 1-year visit to HRD in May 1990. His thermodynamic retrieval has been applied to the Hurricane Norbert (1984) wind field. Also, the vertical gradients of temperature were improved. Development of an airborne-Doppler method to estimate precipitation fall speeds in stratiform clouds has been started.

Significant time has been devoted to an attempt to reconcile the results from two microphysical retrieval methods with the airborne Doppler radar measurements. Method 1 determines precipitation directly from the radar, and the cloud content is then derived by inverting the microphysical parameterization equations. Method 2 solves the continuity equations for total water content and precipitation content simultaneously, and the cloud content is determined from the difference between the total content and precipitation content. Method 1 places the condensation and cloud content maxima $\sim$1/8 of a circumference upwind of those found by method 2. Much of the difference between the methods may be attributable to reflectivity attenuation. However, of equal importance is the inconsistency between the composite wind and radar reflectivity fields, which is caused by the failure of the composites to represent an instantaneous field.

---

[2]R. P. Davies-Jones, "Tornado Dynamics." In *Thunderstorms: A Social, Scientific, and Technological Documentary*. Vol. II, E. Kessler, ed. (Norman: University of Oklahoma Press, 1985), 197-236.

The water budget using the results from method 2 gave fractions of the bulk condensate (evaporated or precipitated as rain) that were quite similar to those from method 1. Thus, these bulk quantities agree better than do the three-dimensional distributions. With the more rapid Doppler scanning possible now that two airborne radars are available, the wind will be much closer to the instantaneous wind field, and, therefore, more consistent with the radar reflectivity field. The agreement among the two methods and the radar and Doppler wind fields is then expected to improve.

Results from the Hurricane Norbert water budget study indicate that the horizontal moisture convergence from .5 km upward in Hurricane Norbert was much less than the observed precipitation. This difference suggests that either inflow into Norbert was in a very shallow layer or that about half of the moisture necessary for the precipitation came from sea surface exchange within the budget volume.

Plans (FY-91)

A method to improve the estimation of vertical velocities within stratiform clouds observed by airborne Doppler radar will be developed.

A manuscript describing the thermodynamic structure of Norbert will be completed.

The inner core Hurricane Emily wind field for 22 September 1987 has been constructed. This will allow the determination of the water budget of a storm that was intensifying rapidly during during the research mission. The thermodynamic retrieval methods developed over the last 3 years will be applied to Emily, and temperature and pressure fields will be retrieved. Retrieval of microphysical distributions will be started.

The retrieval methods that we have developed until now assume that the wind, thermodynamic, and microphysical structures are steady-state. This assumption was made because of the long time required to complete one storm-centered Doppler flight pattern when only one airborne Doppler was available. Because both WP-3D aircraft are now equipped with airborne Doppler radar, more rapid and more frequent scans of the wind field are possible. We have obtained five storm-centered Doppler-wind analyses that are 1/2 h apart during the 1990 hurricane season. Such data will permit us to observe the evolution of the wind field with 1/2-h resolution.

2. Spectral Modeling of a Hurricane With Full Physics

Goal

The long-term goal is the prediction, with physical understanding, 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 using an accurate and flexible numerical method, called the "Spectral Application of Finite Element Representation (SAFER)" method. The two-dimensional horizontal version of QVADIS, on nested multiple domains, is now in use by other HRD projects. The current focus of this project is to construct a two-dimensional model in the vertical plane and to test a new formulation of moist thermodynamics.

Accomplishments (FY-90)

In the history of numerical weather prediction, moisture and moist thermodynamic processes have been treated as secondary additions to the dry atmosphere, and this tradition has been followed by many hurricane models. Even in those models that explicitly calculate mesoscale convection, moist processes are approximated in various ways, so that the assumed procedures in mesoscale models and those in synoptic-scale models are incompatible. A unified formulation of moist thermodynamics is necessary in a hurricane model that must cover all scales.

A new formulation of moist thermodynamics for the use in prediction models has been developed on the basis of strict conservation principles. The temperature and pressure of moist air are not predicted, but are diagnostically determined from predicted mass and entropy. The new formulation cleanly separates the thermodynamic processes from the dynamics. It is believed that this separation will simplify the construction of a hurricane model, both conceptually and numerically. A theoretical paper, "A Thermodynamic Foundation for Modeling the Moist Atmosphere," was published in the *Journal of the Atmospheric Sciences*.

The atmosphere is highly stratified, and the model representation of the vertical structure is important. After a careful examination of available options, the SAFER method has been adopted in the vertical. Although the virtues of the SAFER method have been clearly demonstrated by the success of QVADIS, the physical presence of the earth's surface and the planetary boundary layer introduce new problems when it is applied in the vertical. A modified vertical coordinate that stretches toward the bottom has been selected, and the necessary algorithm for spline-spectral transforms on the stretched coordinate has been developed.

To keep the model computationally affordable, the semi-implicit method of time integration for controlling computational problems associated with acoustic wave propagation and vertical eddy fluxes will be used. Earlier, it was found that the method may be applied to the nested model as a two-stage process of leap-frog prediction and acoustic correction. It was also found, however, that computationally efficient coding of each stage is not a trivial problem. To avoid the costly recalculation of spectral-transform coefficients at every time step, a certain normalization of the prognostic variables and equations is necessary. The proper normalization procedure has now been defined.

The majority of design problems now have been identified and theoretically resolved. Actual coding is in progress.

Plans (FY-91)

As part of developing a three-dimensional moist model, a pilot model in a vertical two-dimensional plane will be studied. This model will give us the first opportunity to test the new thermodynamic formulation in a dynamic system. The efficacy of the semi-implicit method also will be evaluated. The parameterization of certain irreversible processes, such as eddy fluxes and precipitation processes, will be the physically more interesting part of this study.

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

Goal

The objective of this study is the testing of the spectral nesting technique SAFER (see above) in the context of the simplest system of equations that can be used for hurricane track prediction. The model will be initialized with real data and its applicability to operational forecasting of hurricane tracks will be determined. In addition, insight, needed for application of the method to three-dimensional models, will be obtained.

Accomplishments (FY-90)

An analysis and barotropic track forecasting system (nicknamed VICBAR), which uses the spectral nesting technique, has been developed. Winds and geopotential heights at 850, 700, 500 and 200 mb are analyzed using the Lord-Ooyama HRD nested spline analysis code. The barotropic model is then initialized with the vertically averaged winds and heights to produce a 72-h track forecast. Initial data that would allow ~120 forecasts to be made were collected in real-time during the 1989 hurricane season. Track forecasts for about 30% of these cases were run in real-time and made available to the forecasters at the NHC. The remaining cases were run after the season and the results were compared with operational track prediction models. VICBAR had smaller average track forecast errors than other dynamical models and had forecast skill comparable with the statistical-dynamical model NHC83. The latter has been NHC's most skillful model for several years.

A comprehensive study was carrried out, based upon the 120 forecast cases, to determine the optimal method for using the multilevel analyses. Results showed that use of a standard mass-weighted vertical average is superior to use of a variable vertical average. (The variable average was chosen so that the initial storm motion was consistent with the previous storm motion.) Results also showed that it is preferable to include bogus wind observations within 600 km of the storm center to represent the vortex circulation, even in the cases where aircraft data were available. However, this method requires an accurate estimation of the initial vortex motion.

Other studies were performed to determine methods for improving the track forecasts. Special satellite winds were obtained from the University of Wisconsin for ~25 cases. Results showed that the extra satellite data reduced the mean forecast errors by ~5%. The model was modified to include time-dependent boundary conditions. Experiments using observed fields on the boundaries showed that improvements of 10% to 20% at 72 h may be possible.

The cases for which ODW observations were available were run with the real-time VICBAR model. With these cases, we tested the impact of including an additional analysis level (400 mb). The inclusion of the 400-mb level resulted in a slight reduction of the forecast error.

The results from the analyses and forecasts were presented at the "Special Session on Hurricane Hugo" of the *70th Annual Meeting of the American Meteorology Society* in Anaheim, California, in February 1990. The VICBAR forecast results were presented at the *44th Interdepartmental Hurricane Conference* in Homestead, Florida, in January 1990.

Plans (FY-91)

VICBAR, with modifications based upon results from the 1989 season, was run during the 1990 hurricane season. The new version includes an additional analysis level (400 mb), the inclusion of Southern Hemisphere data (to 27.5°S), and time-dependent boundary conditions from NMC's global spectral model. Real-time forecasts will be made for 1200 UTC and whenever there are ODW missions. These should be available ~4 to 5 h after the synoptic times (compared with 7 to 8 h in 1989). This improvement resulted from the automation of several parts of the model and the use of a 12-h forecast as a first-guess field. The 0000 UTC forecasts will be run the morning after the synoptic times.

The results from the 1990 season will be submitted for presentation at the AMS *19th Conference on Hurricanes and Tropical Meteorology* (Miami, Florida, May 1991). Preparation of a manuscript describing the VICBAR model and the 1989-1990 results will begin following the 1990 hurricane season.

4. **Initialization of Tropical Cyclone Models**

Goal

The objective of this study is the investigation of methods for initializing tropical prediction models. 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. The application of normal-mode initialization to tropical cyclone simulations is also being studied. 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-90)

The study of normal-mode initialization in a highly truncated axisymmetric hurricane model was completed. 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. A paper describing these results was published in the October 1990 issue of the *Monthly Weather Review*.

An equivalent barotropic model was developed to study the adjoint method. The model uses a standard second-order finite difference scheme (Arakawa Jacobian) and was adapted to run using initial conditions from real data. The model also uses time-dependent boundary conditions. The adjoint model appropriate to the above grid-point model has also been developed. When the adjoint method was tested on a case from Hurricane Hugo (1989), the results were very encouraging. The assimilation of three analyses (at 12-h intervals) produces a model initial condition that has information about the previous track of the storm. As a result, the forecast has very small short-term (12 to 24 h) errors. This study was presented at, and published in the proceedings of, the *International Symposium on Assimilation of Observations in Meteorology and Oceanography* in Clermont-Ferrand, France, in July 1990.

Plans (FY-91)

The main emphasis of this project will be on the adjoint method. To improve the model's efficiency, multigrid software obtained from scientists at Clarkson University (New York) will be installed. This software will reduce the iterations required to solve the elliptic equations during the forward and adjoint integrations. The assimilation procedure requires the minimization of a functional, which, currently, is achieved using the method of steepest descents. This method will be replaced by a conjugate gradient method to further improve the model efficiency. In another modification, the model equations will be imposed as weak, rather than strong, constraints in the present formulation. This technique should spread the error between the model and data more evenly over the assimilation period.

The method will be tested on ~40 cases from the 1989 hurricane season to determine how much improvement might be possible in short-term track forecasts. The assimilation procedure can also be used to establish model parameters. Experiments will be performed to find the optimal Rossby radius of deformation, which prevents the retrogression of the very long waves in the barotropic forecast model.

An abstract describing these results will be submitted for presentation at the AMS *9th Conference on Numerical Weather Prediction* (Denver, Colorado, October 1991). Preparation of a manuscript describing the results from the adjoint method will begin.

Preliminary work to develop a normal-mode initialization scheme for VICBAR (see above) may be started.

5. Asymmetric Evolution of the Hurricane

Goal

The objective of this work is the understanding and prediction of the asymmetric structure and evolution of the hurricane vortex, including its interaction with the large-scale environment. The asymmetries are central to the track prediction problem, as well as to the distribution of winds and convection in a moving vortex. This research will provide increased understanding of the physical processes that affect hurricane motion, and insight into model formulation, interpretation, and initialization for real-data forecasts.

Accomplishments (FY-90)

A multinested numerical model, developed at HRD using SAFER (see above), has been used on the beta plane to investigate the influence of divergence, total relative angular momentum (RAM), and advective nonlinearities on the evolution of a hurricane-like vortex. Results from a barotropic, primitive equation (shallow-water) model, have been published and are summarized below.

During a 120-h simulation, an initially symmetric cyclonic vortex in a resting environment 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. Within a few days, the near-vortex asymmetries reach a near-steady state. The asymmetric absolute vorticity (AAV) is nearly uniform within ~350 km of the vortex center. The homogenization of AAV effectively neutralizes the planetary beta effect, as well as the vorticity associated with an environmental wind.

A three-layer model has now been developed to investigate these processes in a more realistic physical context. 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.

Tests with a symmetric vortex on an f-plane were carried out to evaluate the model's sensitivity to adjustable parameters, including lateral diffusion. Experiments were then made with an initially symmetric vortex on a beta plane in an environment at rest. Preliminary results indicate that the oscillation of RAM and homogenization of AAV found with the barotropic model are also present in the three-layer simulations.

Results of this research were presented at a seminar at the University of Illinois.

Plans (FY-91)

Further experiments with the three-layer model will be designed to evaluate the effect of internal and external sources of heat and momentum on the evolution of the hurricane. Particular attention will be given to the effects of variations in environmental potential vorticity on vortex motion and intensification. The effects of vertical wind shear on vortex evolution will be investigated.

The three-layer model will also be used in real-data experiments initialized from analyses derived from the HRD project "Objective Analysis of the Hurricane and Its Environment" (section 6). Data from

Hurricanes Josephine (1984) and Gloria (1985) will be used to test the model's ability to forecast hurricane tracks out to 72 h. Comparisons will be made with forecasts from VICBAR. Sensitivity experiments will be made to test the forecast's dependence upon the details of the model's vertical structure and thermodynamic parameters, including sea-surface temperature.

Results of the research will be presented at the AMS *19th Conference on Hurricanes and Tropical Meteorology* (Miami, Florida, May 1991).

6. Objective Analysis of the Hurricane and Its Environment

Goal

This research uses the HRD Spline Objective Analysis (Lord-Ooyama) scheme and data obtained from HRD's ODW experiments. The analysis scheme is able to incorporate data from a wide variety of platforms, such as airborne Doppler radar, ODW's, NOAA WP-3D and other reconnaissance aircraft, rawinsondes, and satellites. The analysis scheme is used to produce three-dimensional wind and thermodynamic analyses. These analyses are then used for diagnostic and prognostic studies of hurricane motion.

The objective analyses are also used to evaluate the quality of VAS data over the tropical Atlantic basin and to determine optimal ways to incorporate the VAS data in the analysis of the hurricane environment.

Accomplishments (FY-90)

A manuscript, "Some Comparisons of VAS and Dropwindsonde Data Over the Subtropical Atlantic," authored by HRD staff, and by NWS staff at the University of Wisconsin, was published in the September 1990 *Monthly Weather Review*.

Three-dimensional objective wind analyses were completed for the third (final) ODW day in Hurricane Josephine (1984). A manuscript, "Dropwindsonde Observations of the Environmental Flow of Hurricane Josephine (1984): Relationships to Vortex Motion" was accepted for publication in the *Monthly Weather Review*.

Three-dimensional objective wind analyses were completed for the ODW day in Hurricane Gloria (1985). This set of analyses represents the most complete multiscale, three-dimensional wind analysis of a hurricane and its environment constructed to date and is the first to make full use of the HRD multinested analysis algorithm. The analysis scales (filter wavelengths) vary from 9° latitude on the largest of nine meshes to 0.15° on the smallest. The analyses are being used in diagnostic and prognostic (VICBAR) studies relating to the motion of the vortex, and also being used in the development and testing of the HRD three-layer asymmetric hurricane model (section 5, above).

Work has started on wind analyses for the Hurricanes Emily (1987) and Florence (1988) ODW cases. Processing and editing of airborne Doppler radar data for the Florence experiment on 8-9 September 1988 has been completed, and preliminary nested analyses on 19 pressure surfaces have been completed for use in data quality control. Preliminary analyses (excluding Doppler data) have been started for the two Emily cases on 22-23 and 23-24 September 1987.

Plans (FY-91)

Research with the Gloria nested analyses will continue. A manuscript describing the multiscale structure of Hurricane Gloria will be written and submitted to the *Monthly Weather Review*. Emphasis in the manuscript will be on the motion of the vortex. Results of this research will be presented at the AMS *19th Conference on Hurricanes and Tropical Meteorology* (Miami, Florida, May 1991) and published in the proceedings.

Work on the wind analyses for the Emily and Florence cases will continue. Airborne Doppler radar data for the Emily cases will be processed and included in the analyses. The preliminary analyses/data quality control phase will be completed for the three cases and cross-sectional analyses will be started.

7. Tropical Climate Studies

Goal

This project will establish a climatology and time history of quasi-steady and propagating disturbances in the atmosphere over the tropical Atlantic. The relationship of the long-term variability of winds and other tropospheric features to climatic fluctuations and hurricane cycles will be established.

Accomplishments (FY-90)

A study to establish the Atlantic hurricane cycles and tropical wind variability associated with intraseasonal oscillations, as well as the predictability of the cycles, is in progress. Wind observations for 1980 to 1989 are used from the NHC's tropical analysis. The data are filtered to remove periods less than $\sim$15 days, and then are sampled once every 5 days. The tropical analyses include winds at both an upper (200 mb) and lower (near-surface) level, from the equator to $\sim$45°N and from $\sim$5° to 125°W. The winds are filtered into three bands. The "monthly" band (50 to 85 days) includes variability on the month-to-month (60-day) time scale; the 30 to 55 day band corresponds to the time scale of the well-known global tropical oscillation; the "intermediate" band (18 to 29 days) comprises shorter period oscillations. Maps of energy and significant spectral peaks in the bands at both the lower and upper levels were made for summer (May-October) and winter (November-April).

The most energetic signals occur during winter. An **e**mpirical **o**rthogonal **f**unction (EOF) analysis was made of the upper level winds over the Atlantic/eastern Pacific area for the winter. A Hilbert transform was used to study the amplitude and phase behavior of the dominant complex EOF modes. In the winters of 1980-81, 1984-85, and 1985-86, the modes in the monthly band were dominated by three events. The structure of the dominant mode (a nonpropagating dipole) corresponds to global and regional modes of intraseasonal variability found by other investigators. Teleconnection patterns and the first two dominant modes of variability in the intermediate band during winter represent east-west oriented wavetrains, which have also been found by other investigators. The second mode, however, shows evidence of southeast propagation, which was not found in earlier studies and is confirmed by point-to-point correlation statistics. Orthogonal rotation of the modes was required to correctly represent the propagation characteristics.

An objective index of the global tropical 30 to 55 day oscillation has been obtained from scientists at the University of Wisconsin. This tropical signal is strong over the tropical eastern Pacific, but is generally weak over the Atlantic. Thus, the signal is only weakly correlated with Atlantic tropical storm activity. No significant spectral peak is found in Atlantic tropical storm activity on intraseasonal time scales. The dominant regional (rotated) mode of variability in the 30 to 55 day band at 200 mb is, however, strongly correlated with the global signal during the summer.

A new investigation to better understand the relationships between large-scale flow features and the intensification of tropical cyclones was started. Parameters (including sea surface temperature, vertical wind shear, latitude, speed of motion, previous 24-h intensity change, and distance to land) were correlated with future intensity changes using analyses from the 1989 hurricane season. One goal of this study is to develop a statistical model for forecasting hurricane intensity changes. A program has been written to produce 12-, 24-, 36-, and 48-h intensity forecasts using input from the VICBAR analyses and forecasts. A second goal is to use the relationships between the large-scale flow and hurricane intensification to better understand the interannual variability of Atlantic tropical cyclones.

Plans (FY-91)

The study of intraseasonal variability over the tropical Atlantic will continue. The EOF analysis of the winds will be completed for the summer upper level modes of variability, and for the low-level and coupled upper/lower level modes for summer and winter. The results for the monthly (50 to 85 day) and 30 to 55 day bands will be compared with a combined 30 to 85 day analysis. An oblique rotation of the EOF's may be explored to confirm the results of the orthogonal rotations. Complete spectra will be made of the unfiltered Atlantic tropical winds for selected years for the summer and winter seasons.

The analysis will be extended to include **o**utgoing **l**ongwave **r**adiation (OLR) to relate convective activity to the wind fields. Sea-surface temperature variability may also be included in some aspects of the study. As time permits, the relationships of the dominant modes of variability during the summer to tropical storm cycles in the Atlantic and eastern Pacific will be evaluated. The relationship of the global tropical 30 to 55 day oscillation to eastern Pacific tropical storm activity also will be evaluated.

The study of the intensification of tropical cyclones will continue. The data base for the development of the statistical relationships will be expanded to include all possible cases from the 1990 season, as well as analyses of archived observations from the 1988 season. The **s**tatistical **h**urricane **i**ntensity **p**rediction **s**cheme (SHIPS) developed from the 1989 data will be run in real-time, and the results will be made available to the forecasters at NHC. New predictors also will be tested, including upper level eddy angular momentum fluxes and eye diameter.

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 and enhance awareness of tropical cyclones and to promote preparedness and mitigation efforts in tropical-cyclone-prone areas.

Accomplishments (FY-90)

The computer-assisted instructional (CAI) component (cognitive module) of the cognitive and affective learning model (CALM) model was modified based upon suggestions received from teachers and students of local middle and senior high schools that participated in proof-of-concept testing programs, and meteorologists (HRD and NHC) who reviewed, and/or participated in, the project.

In concert with a simple scheme, designed to test the hypothesis that "tropical cyclone awareness was created/enhanced by the educational treatment" (i.e., CALM's cognitive and affective modules), 145 students from local schools participated in the program.

Analysis schemes were developed to statistically compare the results from these student groups which were given, respectively, no instruction, standard instruction, and instruction based upon CALM. Preliminary analyses indicate that learning took place in the STANDARD and CALM groups.

The proof-of-concept program was designed to instruct and test a random sample (cross section) of the school's student population. However, pre- and post-test scores of all groups showed marked differences in the cognitive abilities of the participants. Some students were typically on the "low end" of the academic scale (students "forced" to take at least one science class to meet graduation requirements). Other student participants were enrolled in advanced science or research courses.

Plans (FY-91)

Suggestions and comments from teachers and students will be used in an effort to improve the program.

Analysis of the data collected during FY-90 will be completed. At the request of the Pinellas County (Florida) Emergency Management Division and local schools, the CALM program will be conducted in FY-91. Additional data will be collected to test the program's research hypotheses.

A teacher's guide and a student's workbook may be developed. CAI units will be revised. Results of the study will be prepared for publication. Instructional materials will be modified for use in adult education programs as requested by Emergency Management officials in Pinellas County, Florida.

9. Storm Surge

Goal

The goal of the research is the adaptation of the SLOSH (**s**ea, **l**ake, and **o**verland **s**urge from **h**urricanes) storm surge model to specific bays and estuaries for operational storm-surge prediction.

Accomplishments (FY-90)

Hypothetical storm-surge simulations were completed for the Florida regions of Cape Canaveral, at high tide, and Charlotte Harbor. Preliminary atlases were also completed for these basins.

Plans (FY-91)

Hypothetical hurricane-storm surge simulations will be made for revised and enlarged Tampa Bay and Palm Beach, Florida, basins. Preliminary atlases for these basins will be completed.

10. GALE

Goal

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

Accomplishments (FY-90)

HRD collected data from NWS radars in the Carolinas during GALE in 1986. Much of the precipitation data were organized in convective and stratiform rainbands. The data indicate that many GALE rainbands formed over the Gulf Stream. Reports from NWS radars and lightning reports from the State University of New York at Albany lightning network showed maxima over the Gulf Stream during GALE.

Ten of the GALE rainband cases that heavily contributed to the radar reflectivity maximum were studied in detail. Echoes that were not organized as rainbands only accounted for 6% of the radar reflectivity reports >40 dBZ. Western rainbands (WR) also contributed to the Gulf Stream maxima of lightning and radar reflectivity. At least 40% of the WR weakened while crossing over the coastal shelf waters before they reintensified over the Gulf Stream. The maximum of convective activity, therefore, resulted from both the formation of new rainbands over the Gulf Stream and from reintensification of preexisting rainbands.

GALE rainbands were usually associated with synoptic-scale weather systems. Time series of temperature, moisture advection, divergence, vertically integrated liquid water, and kinematic vertical velocity were computed from soundings at the triangle of stations with corners at Charleston, South Carolina, and Greensboro and Cape Hatteras, North Carolina. The rainband cases were usually preceded by warm and/or moist advection. In the absence of rainbands, cold advection and subsidence dominated the region.

Plans (FY-91)

The paper on GALE rainbands will be completed and submitted to the *Monthly Weather Review*.

11. EMEX

Goals

The primary scientific objective of the Equatorial Mesoscale Experiment (EMEX) is a definition of the vertical profile of atmospheric heating produced by cloud clusters in the oceanic area around northern Australia. The accurate determination of this profile is of critical importance for 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-90)

HRD has completed the merging of airborne Doppler radar data for the EMEX research flights. The merge tapes have been sent to the University of Washington (UW) for subsequent vertical incidence and pseudo-dual-Doppler analysis. UW scientists have completed analyses for all missions in EMEX. The analyses were classified as: convective (19 cases); stratiform (20 cases); and transition (21 cases).

The airborne Doppler radar data in convective regions show a transition from low-level convergence with upper level divergence in the convective regions to upper level convergence with low-level divergence in the transition region, to midlevel convergence with both upper and lower level divergence in the stratiform region. The shape of the divergence profile in the transition region suggests that upper level up- and downdrafts may play an important role in the mass budget of the tropical mesoscale convective systems (MCS's). A paper describing these results was presented at the AMS *4th Conference on Mesoscale Processes* in June 1990. A joint UW/HRD manuscript summarizing the EMEX experiment and these analyses is in preparation.

Plans (FY-91)

The principal effort this year will be the completion of a case study from the EMEX data and preparation of a manuscript that will focus on the kinematic structure of an EMEX MCS. HRD will continue its interaction with the UW group. Work to refine vertical velocity measurements from the vertical incidence data will be emphasized.

12. TOGA COARE

Goal

Understanding of global climate change requires a better specification of the coupling of the ocean and atmosphere. This is particularly important in the western Pacific warm pool region (centered just south of the equator at 155°W). Processes that occur in this region are fundamental to the global atmosphere-ocean system. The Tropical Oceans Global Atmospheres (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) has been created to gain greater insight into the physical nature of these interactions.

Accomplishments (FY-90)

The TOGA COARE field program is scheduled for 1992. Much of the current effort is in the design of flight plans for three research aircraft that are projected to participate in this experiment. Plans include use of the NOAA WP-3D research aircraft. The formal mechanism for the design of the aircraft research program is the TOGA COARE Convection Working Group.

A specific scientific concern is modification of the warm pool air-sea interaction processes by convective and mesoscale systems. The problem is being approached as a logical outgrowth of EMEX. We are attempting to identify the problems encountered in EMEX and the areas of research that could not be addressed with the EMEX data set. There is a clear need for improved:

- Measurements of thermodynamic variables, including moisture and water content, in cloud and precipitation, to describe the thermodynamic structure of MCS's

- Measurements of precipitation particle characteristics, including habit, size, and fall speed, particularly at high altitude, to help with the interpretation of the airborne Doppler radar data

- Sampling of the boundary layer fluxes to improve budget computations

Some of these items can be addressed through better experimental design, while others require improvements in instrumentation.

A proposal to the TOGA COARE Project Office to complete the experiment design and to participate in the field program is nearing completion.

Plans (FY-91)

Much of the work will be focused upon completion of the experiment design. We will be building on our experience in EMEX and in hurricane research flights to design efficient flight patterns. Many of these ideas will be tested using data collected in hurricane research flights.

13. Observational Studies of the South Florida Sea Breeze

Goal

The purpose of this research is improvement of the understanding of the sea breeze circulations that initiate much of the deep convection that forms during the afternoon over the Florida peninsula during the summer.

Accomplishments (FY-90)

A climatological study of the sea breeze circulation of south Florida and the lake breeze of Lake Okeechobee is in progress. The main data set is visible satellite imagery recorded at half-hourly intervals by NHC's McIDAS (Man-Computer Interactive Data System) and archived on magnetic tape at HRD. The satellite imagery has a horizontal resolution of ~1 km and includes the Florida peninsula south of Melbourne and Tampa. Daily 1200 UTC radiosonde observations are also being saved for West Palm Beach. The data archiving began on 1 June 1990 and will end on 30 September 1990. The research focuses on those days with well-defined sea breeze circulations. The sea breeze days are categorized by the low-level wind direction and speed and midtropospheric humidity at West Palm Beach.

Plans (FY-91)

The typical positions of the sea and lake breezes as a function of time of day and low-level wind speed will be established. Previous studies of the sea breeze circulations over the Florida peninsula have identified preferred patterns of radar echoes, thunder, and lightning after the formation of deep convection. This study emphasizes the mesoscale organization of the cloud patterns before the onset of widespread deep convection. Convective activity will be noted in areas where the sea and lake breezes intersect. The region downwind of Lake Okeechobee is frequently suppressed until late in the day. The extent of the area of suppressed conditions will be correlated with low-level wind speed and midtropospheric humidity. A video tape of satellite images that illustrate typical sea and lake breeze conditions will be prepared and copies of the video will be provided to NWS offices in South Florida. A paper will be prepared for *Monthly Weather Review*.

14. Climate and Global Change Program: Ground Truth for Spaceborne Rainfall Estimates

Goal

The global measurement of precipitation is a prime objective of NOAA's Climate and Global Change Program. Remote sensing techniques are being investigated to monitor global precipitation. The majority are from spaceborne platforms that need "ground-truth" observations of rainfall to calibrate their estimates. The only feasible way of approaching the problem is through the use of aircraft such as the NOAA WP-3D. This work addresses the development and application of a technique developed by D. Atlas and colleagues (height-area rainfall technique, HART) to provide a global precipitation data base that could be used as ground truth for the spaceborne observations.

Accomplishments (FY-90)

The research will use the large volume of radar and precipitation probe data gathered on NOAA WP-3D research flights to construct a data base. Good airborne radars and precipitation probes are essential to provide accurate rainfall estimates using the HART method. The Knollenberg probes on the NOAA WP-3D are capable of measuring the rain rates on flights where the aircraft remains below the altitude of the melting layer. At the same time, the airborne radar system records the reflectivity structure of the rain, insuring both are sampling the same population. Preliminary results of a study to evaluate the HART method of rainfall estimation in hurricanes using the WP-3D radar and Knollenberg rain data collected over the last 10 years indicate that the method works well.

A data base of rainfall estimates for hurricanes using the Knollenberg data has been started and airborne data from the lower fuselage radar for the same flights are being processed.

Plans (FY-91)

The airborne radars will be used to measure the areas and tops of the echoes (to further develop, calibrate, and evaluate the HART method for measuring area-average rainfall). The following tasks are planned.

The vertical profiles of reflectivity in various regions of the hurricane will be measured. The WP-3D can measure both the vertical and horizontal reflectivity distribution within the sample rain system. That, with the capability of measuring in-situ cloud physics, makes the WP-3D the perfect tool for investigating the variation of the computed Z-R relationship with altitude and range from the radar.

It will be necessary to distinguish between stratiform and convective precipitation. As yet, the rainfall data have not been stratified between these precipitation types to reduce the variance in estimates of the distribution of rain. Research on mesoscale precipitation systems over the last 10 years suggests that this may be an important stratification.

The data must also be stratified by range and radar beamwidth. These parameters, with the radar beam geometry, make up the majority of the variance in the remotely sensed precipitation estimates.

To provide alternative methods to measure rain rate statistics and provide "air truth," a method will be evaluated to use the Doppler radar at vertical incidence (or in the mirror image mode) to deduce rain rate from a combination of reflectivity and mean Doppler velocity.

COOPERATIVE RESEARCH PROJECTS

1. <u>Desert Research Institute, University of Nevada System</u>

Principal Investigator: Dr. John Hallett

Project: Electrification and Precipitation Processes in Tropical Convection

a. Analysis has been carried out of the electrical and cloud characteristics of the eyewalls of hurricanes penetrated by the NOAA WP-3D aircraft during the last 3 years [Hurricanes Allen (1980), Emily (1987), Gilbert (1988), Gabrielle (1989), and Hugo (1989)]. We have found significant vertical components of electric fields in the eyewall region that are related to the magnitude of the vertical velocity and the presence of supercooled cloud near the -5° to -10°C level. Laboratory experiments suggest that the interaction of graupel (soft hail) and ice crystals in the presence of supercooled cloud is necessary for charge separation to occur; this hypothesis is being investigated.

b. Analysis has been carried out of radar and cloud physics data from NOAA WP-3D flights in maritime cumuli near the Bahamas in September 1988 and 1989. This study distinguishes between cases where precipitation is formed at lower levels by droplet coalescence down to -5° to -10°C, and falls out, and those cases where such precipitation is carried upwards in vertical velocities >5 m s^{-1} to participate in ice phase evolution aloft. The vertically pointed tail radar gives intensity and particle velocity above and below flight level. These data are related to vertical velocity and particle phase and size distributions that are measured directly at flight level. These observations will ultimately enable the estimation of vertical profile of latent heat absorption and release in the cloud.

c. The vertical component of electric field has been measured by two field mills mounted on the top and bottom of a NOAA WP-3D (N42RF). One problem is that the aircraft self-charges negatively, even in clear air, which limits the precision of measurement to ~10 times the fair weather field. It is possible to infer aircraft charge (proportional to the mean of the two readings) and ambient vertical electric field (proportional to the difference of the two readings). Asymmetry of the aircraft is acounted for by actively charging it during clear-air flight. The absolute values obtained are subject to the uncertainty of assuming a cylindrical shape (a factor of 1.5 at most), which is small compared with the changes observed on transition from all-water cloud to ice phase precipitation, a factor of 100 to 1,000. A major problem in construction of the mills has been to ensure that they remain waterproof in the heavy downpours, not only during flight, but also on the tarmac. This difficulty was overcome by installing a specially designed seal on the rotator drive shaft. Additional mills will be added to provide the horizontal component for flights next season.

d. An induction ring probe has been developed and mounted on the wing tip of one NOAA WP-3D. This ring is designed to measure the sign and charge of individual precipitation particles during their passage through it. It is intended to develop software to reject spurious charges on splash particles during flight. The major design problem with this instrument has been engine-induced vibrations, which were close to the particle passage time of 1 millisecond. The new probe was flight-tested in September 1990 and gave a noise level, at typical penetration speed (130 m s^{-1}), equivalent to 10°-12°C. Development of this probe to further reduce noise and give real-time readout of precipitation charge density (C km^{-3}, +,-) is planned for next season. The use of the electrical data lies in assessing the overall intensity of the convective processes remotely (from satellite or by lightning time of arrival/intensity) and using this information to predict development. This aspect of the work is being carried out in collaboration with Dr. C. P. R. Saunders of the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K.

Related Publications

BLACK, R. A., and J. Hallet, 1990: Electric field and microphysical measurements in vigorous hurricane eyewalls. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, 1990, San Francisco, Calif., 662-665.

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

Hallett, J., and P. T. WILLIS, 1990: The development of precipitation in isolated maritime cumulus. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, 1990, San Francisco, Calif., 74-79.

WILLIS, P. T., and J. Hallett. Microphysical measurements from an aircraft ascending with a growing isolated maritime cumulus tower. *J. Atmos. Sci.*, 47 (Accepted)

Related Work

This work is complemented by laboratory studies in the development of the ice phase in the atmosphere supported by a grant from the Meteorology Division of the National Science Foundation at the Desert Research Institute. The collaboration with UMIST is supported by the Natural Environmental Research Council, U.K.

2. National Center for Atmospheric Research

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

Project Scientists: Dr. Andrew Heymsfield
Mr. Gregory Stossmeister

Project: Hurricane Rainbands: Mesoscale and Convective-Scale Structure

Tropical Storm Isabel (1985)

G. Stossmeister and G. Barnes have analyzed 44 radial passes made by the two NOAA/AOC WP-3D's over a 3-day period in Tropical Storm Isabel (1985). The storm did not achieve hurricane intensity. Reflectivity measurements show that the convection surrounding the original circulation center collapsed, but the convection in a rainband 80 km from the original center intensified. This intensification led to a lowering of the surface pressure by several millibars over a 20 to 40 km horizontal distance. The lowering of pressure was associated with unusually warm, dry air, indicative of subsidence. Analysis of boundary layer winds revealed that a new circulation formed at this location and became the center for the entire tropical storm. The new center formed under the downwind anvil, not in the strong cumulonimbi of the rainband. The behavior of Isabel suggests that large changes in track for depressions and storms may be caused by the creation of a new center, rather than by unusual accelerations and decelerations of the center.

Tropical Storm Irma (1987)

During EMEX, the NOAA/AOC WP-3D, NCAR Electra, and COSSA F-27 probed a rainband in developing Tropical Cyclone Irma (1987). G. Barnes, E. Zipser (Texas A & M University) and B. Ryan

(Commonwealth Scientific and Industrial Research Organization, Australia) are using these aircraft, as well as radar and rawinsondes from nearby land stations, to assemble a view of the thermodynamic, kinematic, and reflectivity structure of this wide rainband. The goal is the determination of whether rainbands, during the early stages of the tropical cyclone life cycle, help or hinder the intensification process.

The analyses demonstrate that the rainband was supported by an unusually wide (50 km) zone of convergence in the subcloud and lower cloud layers. Temperature data show that there was 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 existed at 1.5 km MSL (mean sea level) in the central part of the rainband. The vortex was not well developed at this time, with the tangential winds decreasing to 5 m s^{-1} by 5 km MSL.

The rainband contrasted with other convectively active bands that were studied in Hurricanes Floyd (1981) and Earl (1986) in that low-level flow did not pass through the band at a large crossing angle. Instead, the flow became more parallel to the flow in Irma. The band, unlike the other mentioned cases, did not exist in a strong horizontal pressure gradient typical of the inner 150 km of a mature tropical cyclone. There was also no increase in equivalent potential temperature (θ_e) across the band. We believe that the environment was so moist as to limit cold downdraft production or large decreases in θ_e. The net result of the band was to make the flow more tangential, but without substantially reducing the energy of the inflow. This resulted in a longer trajectory for the inflow, and at a higher speed that would favor larger energy transfers from sea to air. In the early stages, the rainband would have a tendency to enhance vortex intensification.

Hurricane Gilbert (1988)

On 12 September 1988, both NOAA/AOC WP-3D aircraft completed a mission designed to obtain the reflectivity, thermodynamic, kinematic, and dynamic fields associated with an intense convective rainband 160 km southeast of the circulation center of Hurricane Gilbert. Nineteen low-level (300, 450, 720, and 1,500 m) passes normal to the major axis of the rainband revealed a remarkable increase in the θ_e of the inflow. The increase was >10 to 15 K over a 50 km trajectory. Such increases have been observed near the eyewall where the winds also undergo a rapid increase, but changes of this sort have not been witnessed at such large distances from the circulation center.

G. Barnes, with M. POWELL and P. BLACK, intend to examine the energy budget of the inflow layer to estimate the heat and moisture fluxes at the sea surface and the top of the mixed layer. These calculations will be used to assess the accuracy of the assumed transfer coefficients used in the bulk aerodynamic equations. The role of the overlying anvil and accompanying stratiform rain in preventing development of moist convection during the early stages of the trajectory will also be explored. Gilbert became the most intense hurricane on record for the Caribbean Basin, and it may be partially due to the dramatic increase of inflow θ_e.

Microphysics of Hurricanes

A. Heymsfield and P. WILLIS are examining the microphysical trajectories in Hurricane Emily (1987). A very high-resolution three-dimensional Doppler-radar wind analysis is used as input to a detailed microphysical model of hydrometeor evolution. Particle habits and sizes are initiated based upon radar reflectivity and in-situ particle data. As the hydrometeors are advected, they evolve in response to the input thermodynamic data.

The essential details of the composite radar reflectivity pattern observed in the storm can be explained almost entirely by the trajectory analysis. For example, trajectory analysis clearly shows that the reflectivity cores are directly related to the growth and descent of particles that are produced in active deep convection, expelled in the upper level outflow, transported in more stratiform regions, and finally reincorporated into the eyewall convection. Work continues on this topic in FY-91, with the goal of trying to understand the role of particle trajectories in the evolution of this hurricane.

Related Publications

Barnes, G. M., 1989: Summary of the 18th Conference on Hurricanes and Tropical Meteorology, May 16-19, 1989, San Diego, Calif. *Bull. Amer. Meteorol. Soc.*, 71 (4), 558-570.

Barnes, G. M., 1990: A convective cell in a hurricane rainband. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, San Francisco, Calif., 672-678.

Barnes, G. M., J. GAMACHE, M. A. LeMone and G. J. Stossmeister, 1990: A convective cell in a hurricane rainband. *Mon. Weather Rev.* (In press)

Ryan, B., G. M. Barnes and E. J. Zipser: A wide rainband in developing Tropical Cyclone Irma (1987). (In preparation)

Stossmeister, G. J., and G. M. Barnes, 1990: Initiation of a tropical cyclone vortex. *Ex. Abst., 4th Conf. on Mesoscale Processes*-AMS, June 25-29, 1990, Boulder, Colo., 26-27.

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

WILLIS, P. T., and A. J. Heymsfield, 1990: Microphysical trajectories in a tropical cyclone. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, San Francisco, Calif., 666-671.

3. State University of New York at Albany

Principal Investigator: Dr. John Molinari

Project Scientists: Mr. David Vollaro
Mr. Frank Robasky

Project: Intensity Changes in Hurricane Allen (1980)

We have completed this project and have two manuscripts in preparation. The first describes external influences on Hurricane Allen (1980) and the second is part of an analysis of the value of operational data sets for hurricane studies. F. Robasky completed his M.S. thesis, entitled "Large-Scale Environmental Influences on the Intensification of Hurricane Allen (1980)."

The analysis of Allen showed that its first reintensification was preceded by interaction with an upper level vorticity maximum. Balanced solutions for the secondary circulation induced by the interaction showed that an upward motion maximum shifted from outer radii to the center and apparently triggered the development of a secondary eyewall event, much like that which occurred in Hurricane Elena (1985). The upper level disturbance differed dramatically from the middle latitude trough in the Hurricane Elena study (Molinari and Vollaro, 1989, 1990). In Allen, the trough represented a cyclonic shear zone between the outflow layers of Allen and the early stages of an eastern Pacific hurricane. We conclude that the mechanism for upper level interactions postulated in the Elena case may be quite common, even though the source of cyclonic momentum may differ from case to case.

An additional study nearly has been completed on the general value of operational analyses for studying hurricanes. We have concluded that radial velocity contains significant errors, regardless of resolution of the analysis. Tangential velocity, however, is quite accurate outside of the inner radii. Eddy momentum fluxes are quantitatively different, but qualitatively the same, even when center position and storm motion errors are included. Little benefit was found in the high-resolution (1 ⅛° lat-lon) uninitialized analyses from the European Centre for Medium Range Weather Forecasts (ECMWF) versus lower resolution (2.5°) initialized analyses. Center positions in operational analyses were most accurate using 850-mb vorticity and least accurate in 1,000-mb height, especially during early stages of the storms. Some evidence was also found of greater errors in the Atlantic compared with the Caribbean and Gulf of Mexico, as would be expected from the data source distribution. Overall, it was found that mature hurricanes in the Gulf and Caribbean could be represented well outside the 400-km radius in the ECWMF data sets, except in radial velocity fields. This conclusion holds even if center positions must be determined from the operational analyses, themselves, rather than best-track data. The results suggest that eddy momentum fluxes can be used as predictors of hurricane intensity in an operational framework.

Related Publications

Molinari, J., F. Robasky and D. Vollaro, 1990: Intensity change in Hurricane Allen (1980). (In preparation)

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

Molinari, J., and D. Vollaro, 1990: External influences on hurricane intensity: Part II. Vertical structure and response of the hurricane vortex. *J. Atmos. Sci.*, 47, 1902-1918.

Molinari, J., D. Vollaro and F. Alsheimer, 1991: Excitation of secondary eyewalls by external interactions. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla. (Accepted)

Molinari, J., D. Vollaro and F. Robasky, 1990: On the use of operational analyses for tropical cyclone research. (In preparation)

4. State University of New York at Albany

Principal Investigator: Dr. John Molinari

HRD Co-Investigator: Dr. HUGH E. WILLOUGHBY

Project Scientists: Mr. Frank Alsheimer
Mr. David Vollaro

Project: Analysis of a Secondary Eyewall Event

The goals of this project are analyses of the: (a) large-scale environmental influences on Hurricane Danny (1985), much like in our previous studies, and (b) inner core data to gain an understanding of the connection between the two. In the latter, H. WILLOUGHBY has processed the data into 4-km averages for each radial leg and in gridded form at 6-hourly intervals.

On the large scale, we have found that a large-amplitude, upper tropospheric middle latitude trough interacted with the early stages of Danny at the time an eyewall formed 150 km from the center. We strongly suspect that this eyewall was excited by the external interactions and will be attempting to support that conclusion in the coming months.

WILLOUGHBY (1990) has described the wind and height field evolution at inner radii in Danny, which show a single contracting eyewall that accompanies the intensification of the storm to hurricane strength. With WILLOUGHBY, we will be examining other aspects of this process, including the evolution of θ_e and vertical motion. The goals are an understanding of how external forcing can excite an outer eyewall and determination of the extent to which simple models of hurricane intensification describe the process observed in Danny.

5. 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 a C-band Stepped-Frequency Microwave Radiometer (SFMR) to remotely measure ocean surface wind speed and rain rates in hurricanes. For the past 2 years, a focused effort has been spent on the development of software for the surface wind speed/rain rate algorithm to obtain a real-time graphic display of the wind speed time series. This effort appears to be successful, except for some minor instrument degradation due to age. At the end of the 1990 hurricane season, the SFMR will undergo thorough testing and calibration, with some replacement of components if the budget permits.

The Special Sensor Microwave/Imager (SSM/I) was launched in 1987 to provide similar wind speed measurements from space. The SSM/I is much more sensitive to errors introduced by the atmosphere than is the SFMR. To assess the magnitude of these errors, the SFMR was used as "ground truth" to compare wind speed as derived from the SSM/I. This exercise appears to have led to an improvement in the SSM/I measurement as atmospheric attenuation increases.

The SFMR has flown in a P-3 during every hurricane season. At the end of 1989, it had flown 74 missions, with only one minor hardware failure. Negotiations are now under way with NOAA/AOC personnel for the installation of a C-band precision radar, or scatterometer, to remotely measure the wind vector over the ocean.

Related Publications

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

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

Tanner, A. 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., P. G. BLACK, C. T. Swift and K. St. Germain: Surface wind speed and rain rate estimation in hurricanes using airborne microwave spectral radiometer measurements. *J. Atmos. Oceanic Tech.* (In preparation)

6. Cooperative Institute for Marine and Atmospheric Science, University of Miami

Principal Investigator: Dr. Roger Lhermitte

HRD Co-Investigator: Mr. PAUL T. WILLIS

Project: Small Doppler Radars as Precipitation Gage for TRMM Ground Truth

The Tropical Measuring Rainfall Mission (TRMM) is a space mission with the objective of measuring tropical rainfall to achieve a better understanding of the earth's climate. Tropical rainfall represents the major energy input into the atmosphere, and thus is the key to understanding a myriad of atmospheric dynamic and climate mechanisms. The TRMM validation and ground truth are a very important part of the program. We propose to test several Doppler radar techniques for point precipitation measurement that have direct application to the TRMM validation program. The proposed techniques have the potential for supplementing ocean measurements and for contributing significantly to the validation of TRMM data over ocean areas.

7. University of Oklahoma

Principal Investigator: Dr. Howard B. Bluestein

Project Scientist: Mr. Sam Contorno

Project: Analysis of the Landfall of Hurricane Gilbert (1988)

Surface and upper air data from 18 September 1988 were objectively analyzed using the GEMPAK software package. It was found that the analysis was not good enough to diagnose the quasigeostrophic vertical motion field, owing to lack of data in the Gulf of Mexico and the paucity of data in Mexico. We then obtained gridded nested grid model (NGM) data from NCAR and converted them into a form that is amenable to further analysis. Serious problems were encountered with the surface data. Subjective analysis of the actual data indicated that temperature gradients were strongest at the surface, near a pressure trough. On the other hand, the NGM analyses distorted the surface temperature field so badly that warm-front-like features evident in the subjective analyses were absent. We found that the temperature analyses at 1,000 and 950 mb were too warm because of the manner in which the temperature data had been interpolated down from sigma surfaces. We decided to use the observed sea-level pressure estimates and surface temperatures to determine iteratively a hydrostatically consistent temperature field at the 1,000- and 950-mb surfaces, which are near or below the ground level in Texas.

There are no papers in preparation yet. The work is still in progress.

8. University of Washington

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

Project Scientists: Mr. Brian Mapes
Ms. Chungli Wang

HRD Co-Investigators: Dr. FRANK D. MARKS, JR.
Dr. JOHN F. GAMACHE

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

During the past year, we have continued our research on the Hurricane Norbert (1984) and EMEX flights.

Two manuscripts on the airborne Doppler radar observations of Hurricane Norbert have been submitted for publication. The first paper is a kinematic study of the inner core region of the storm. It is the first study of hurricane wind fields with enough detail and coverage to document not only the mean symmetric vortex structure, but also the asymmetric components of the winds. It is found that the inflow and outflow to the storm are affected strongly by the horizontally asymmetric perturbation wind field and the vertically varying mean wind as well as the mean vortex.

The second paper examines the distribution of ice particles in the upper levels of the storm in relation to the Doppler-observed flow patterns. This study is the first to map the horizontal distribution of ice particle characteristics in a hurricane. It is found that the microphysical structure of the inner core region of the storm can be understood by considering the eyewall region as a producer of two types of ice particles: heavier graupel that falls out in the region of the radius of maximum winds and lighter weight snow that is advected by the radial, as well as the tangential, winds.

We have continued to focus on the Doppler-observed winds in 10 tropical cloud clusters investigated on 10 flights in EMEX. B. Mapes has developed a method for deriving the vertical profiles of divergence over selected mesoscale regions in each storm. About 80 to 90 regions have been examined by this technique. These profiles document the unique kinematic structure of three types of regions in the cloud clusters; that is, convective, stratiform, and regions that are changing from convective to stratiform structure. A preliminary report of this work was presented by Mapes and Houze at the AMS *4th Conference on Mesoscale Processes* (June 1990, Boulder, Colorado) and two manuscripts are in process. A thesis on this work was completed by Wang (1990).

Related Publications

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

GAMACHE, J. F., F. D. MARKS, JR. and R. W. BURPEE, 1987: Equatorial Mesoscale Experiment (EMEX) data inventory. NOAA, AOML/HRD, 4301 Rickenbacker Causeway, Miami, Fla., 120 pp.

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., 1989: Observed structure of mesoscale convective systems and implications for large-scale heating. *Q. J. Roy. Meteorol. Soc.*, 115, 425-461.

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. 98195.

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

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

Mapes, B., and R. A. Houze, Jr., 1990: Divergence profiles in tropical mesoscale convective systems. *Ex. Abst., 4th Conf. on Mesoscale Processes*-AMS, June 25-29, 1990, Boulder, Colo., 202-203.

MARKS, F. D., JR., 1986: EMEX research aircraft plan. NOAA, AOML/HRD, 4301 Rickenbacker Causeway, Miami, Fla.

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. *Prepr., 17th Conf. on Hurricanes and Tropical Meteorology*-AMS, April 7-10, 1987, Miami, Fla., 347-350.

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

Webster, P. J., and R. A. Houze, Jr.: The Equatorial Mesoscale Experiment (EMEX): An overview. (In preparation)

Appendix A: Publications[3]

A.1 In Print

[1] Baik, J.-J., M. DEMARIA and S. Raman, 1990: Tropical cyclone simulations with the Betts convective adjustment scheme. Part I: Model description and control simulation. *Mon. Weather Rev.*, 118 (3), 513-528.

[2] Baik, J.-J., M. DEMARIA and S. Raman, 1990: Tropical cyclone simulations with the Betts convective adjustment scheme. Part II: Sensitivity experiments. *Mon. Weather Rev.*, 118 (3), 529-541.

[3] Baik, J.-J., M. DEMARIA and S. Raman, 1990: A comparison of deep cumulus parameterization schemes in an axisymmetric tropical cyclone model. *Postpr., Indo-U.S. Seminar on the Parameterization of Subgrid-Scale Processes in Dynamical Models for Medium-Range Prediction and Global Climate*, Aug. 6-10, 1990, Pune, India.

[4] BLACK, P. G., and F. D. MARKS, JR., 1990: Aircraft penetration of a hurricane "suction vortex" in Hurricane Hugo (15 September 1989). *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 55.

[5] BLACK, R. A., 1990: Radar reflectivity - ice water content relationships for use above the melting level in hurricanes. *J. Appl. Meteorol.*, 29 (9), 955-961.

[6] BLACK, R. A., and J. Hallett, 1990: Electrical and microphysical structure of Hurricane Hugo: Results of aircraft penetrations. *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 53.

[7] BLACK, R. A., and J. Hallett, 1990: Electric field and microphysical measurements in vigorous hurricane eyewalls. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, 1990, San Francisco, Calif., 662-665.

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

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

[10] DEMARIA, M., 1990: Normal-mode initialization in a tropical cyclone model. *Mon. Weather Rev.*, 118 (10), 2199-2214.

[11] DEMARIA, M., and S. D. ABERSON, 1990: Forecasting the track of Hurricane Hugo. *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 46.

[12] DEMARIA, M., and R. W. JONES, 1990: The use of aircraft observations in a hurricane track forecast model. *Proc., International Symposium on Assimilation of Observations in Meteorology and Oceanography*-AMS, July 9-13, 1990, Clermont-Ferrand, France, 191-195.

[13] DEMARIA, M., M. B. Lawrence and J. T. Kroll, 1990: An error analysis of Atlantic tropical cyclone track guidance models. *Wea. Forecasting*, 5 (1), 47-61.

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

[14] DODGE, P. P., J. S. GRIFFIN, F. D. MARKS, JR. and R. W. BURPEE, 1990: Interactive analysis of NOAA P-3 aircraft data in support of operational hurricane forecasting. *Proc., 6th International Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*-AMS, Feb. 4-9, 1990, Anaheim, Calif., 245-247.

[15] FRANKLIN, J. L., C. S. Velden, J. KAPLAN and C. M. Hayden, 1990: Some comparisons of VAS and dropwindsonde data over the subtropical Atlantic. *Mon. Weather Rev.*, 118 (9), 1869-1887.

[16] GAMACHE, J. F., 1990: Microphysical observations in summer MONEX convective and stratiform clouds. *Mon. Weather Rev.*, 118 (6), 1238-1249.

[17] Hallett, J., and P. T. WILLIS, 1990: The development of precipitation in isolated maritime cumulus. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, 1990, San Francisco, Calif., 74-79.

[18] Houze, R. A., Jr., B. F. Smull and P. P. DODGE, 1990: Mesoscale organization of springtime rainstorms in Oklahoma. *Mon. Weather Rev.*, 118 (3), 613-654.

[19] Houze, R. A., Jr., B. F. Smull and P. P. DODGE, 1990: Mesoscale organization of springtime rainstorms in Oklahoma. *2nd National Weather Service Heavy Precipitation Workshop*, March 13-16, 1990, Nugget, Sparks, Nev., 12-13.

[20] Lord, S. J., and J. L. FRANKLIN, 1990: The environment of Hurricane Debby (1982). Part II: Thermodynamic fields. *Mon. Weather Rev.*, 118 (7), 1444-1459.

[21] MARKS, F. D., JR., 1990: Evolution of the structure of precipitation in Hurricane Hugo (15-22 September 1989). *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 57.

[22] MARKS, F. D., JR., and P. G. BLACK, 1990: Close encounter with an intense mesoscale vortex within Hurricane Hugo (September 15, 1989). *Ex. Abst., 4th Conf. on Mesoscale Processes*-AMS, June 25-29, 1990, Boulder, Colo., 114-115.

[23] McFadden, J. D., P. G. BLACK and F. D. MARKS, JR., 1990: An encounter with Hugo: The flight of 15 September 1989. *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 54.

[24] OOYAMA, K. V., 1990: A thermodynamic foundation for modeling the moist atmosphere. *J. Atmos. Sci.*, 47.

[25] POWELL, M. D., 1990: Boundary-layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale rainfall and kinematic structure. *Mon. Weather Rev.*, 118 (4), 891-917.

[26] 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 (4), 918-938.

[27] POWELL, M. D., 1990: The wind field of Hurricane Hugo at landfall. *Abst., 70th Annual Meeting of the American Meteorological Society*, Special Session on Hurricane Hugo, Feb. 4-9, 1990, Anaheim, Calif., p. 50.

[28] POWELL, M. D, 1990: Observations of boundary layer structure and mesoscale wind fields in a midlatitude marine rainband during GALE. *Ex. Abst., 4th Conf. on Mesoscale Processes*-AMS, June 25-29, 1990, Boulder, Colo., 55-56.

[29] POWELL, M. D., 1990: Meteorological aspects of Hurricane Hugo. *Hugo, One Year Later, A Symposium and Public Forum*-ASCE, September 13-15, 1990, Charleston, S. C.

[30] POWELL, M. D., and P. G. BLACK, 1990: Meteorological aspects of Hurricane Hugo's landfall in the Carolinas. *Shore and Beach*, Vol. 58 (4), 3-10.

[31] ROSENTHAL, S. L., 1990: Summary of the special sessions on Hurricane Hugo, 70th Annual Meeting of the American Meteorological Society, 4-9 February 1990, Anaheim, California. *Bull. Amer. Meteorol. Soc.*, 71 (9), 1339-1342.

[32] SHAPIRO, L. J., and K. V. OOYAMA, 1990: Barotropic vortex evolution on a beta plane. *J. Atmos. Sci.*, 47 (2), 170-187.

[33] WILLIS, P. T., and A. J. Heymsfield, 1990: Microphysical trajectories in a tropical cyclone. *Prepr., Conf. on Cloud Physics*-AMS, July 23-27, 1990, San Francisco, Calif., 666-671.

[34] WILLOUGHBY, H. E., 1990: Temporal changes of the primary circulation in tropical cyclones. *J. Atmos. Sci.*, 47 (2), 242-264.

[35] WILLOUGHBY, H. E., 1990: Gradient balance in tropical cyclones. *J. Atmos. Sci.*, 47 (2), 265-274.

[36] WILLOUGHBY, H. E., 1990: Linear normal modes of a moving, shallow-water barotropic vortex. *J. Atmos. Sci.*, 47 (17), 2141-2148.

[37] WILLOUGHBY, H. E., B. J. Masters and C. Landsea, 1989: A record minimum sea-level pressure observed in Hurricane Gilbert. *Mon. Weather Rev.*, 117 (12), 2824-2828.

A.2 Accepted

[38] ABERSON, S. D., and M. DEMARIA, 1991: A nested barotropic hurricane track forecast model (VICBAR). *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[39] Barnes, G. M., J. F. GAMACHE, M. LeMone and G. J. Stossmeister: A convective cell in a hurricane rainband. *Mon. Weather Rev.*

[40] BLACK, M. L., R. W. BURPEE and F. D. MARKS, JR., 1991: Vertical motions in tropical cyclones determined with airborne Doppler radial velocities. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[41] BURPEE, R. W., and P. G. BLACK, 1991: Strong surface winds and mesoscale convective systems in the unnamed tropical storm of 1987. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[42] BURPEE, R. W., J. GRIFFIN, J. L. FRANKLIN and F. D. MARKS, JR., 1991: Airborne analysis of observations from a NOAA P-3 in support of operational hurricane forecasting. *Prepr., 7th International Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology*-AMS, Jan. 13-18, 1991, New Orleans, La.

[43] BURPEE, R. W., J. S. GRIFFIN, J. L. FRANKLIN and F. D. MARKS, JR., 1991: Airborne analysis of observations from a P-3 aircraft in support of operational hurricane forecasting. *4th Interagency Airborne Geoscience Workshop*, Jan. 29-Feb. 1, 1991, La Jolla, Calif.

[44] DEMARIA, M., and J. KAPLAN, 1991: A statistical model for predicting tropical cyclone intensity change. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[45] DODGE, P. P., R. W. BURPEE and F. D. MARKS, JR., 1991: Airborne Doppler radar analyses of the core of Hurricane Gilbert. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[46] FEUER, S. E., and J. L. FRANKLIN, 1991: Nested analyses of Hurricane Gloria from dropwindsonde and Doppler radar data. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[47] FRANKLIN, J. L., 1990: Dropwindsonde observations of the environmental flow of Hurricane Josephine (1984): Relationships to vortex motion. *Mon. Weather Rev.* 118.

[48] FRANKLIN, J. L., M. DEMARIA and C. S. Velden, 1991: The impact of Omega dropwindsonde and satellite data on hurricane track forecasts using the VICBAR model. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[49] GAMACHE, J. F., 1991: Inner core budget studies of Hurricane Emily (1987). *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[50] GRIFFIN, J. S., R. W. BURPEE, J. L. FRANKLIN and F. D. MARKS, JR., 1991: Airborne analysis of observations from a NOAA P-3 in support of operational hurricane forecasting. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[51] HOUSTON, S. H., and M. D. POWELL, 1991: Effects of Tropical Storm Marco (1990) on Florida's west coast. *Ex. Abst., 5th Conf. on Meteorology and Oceanography of the Coastal Zone*–AMS, May 6–10, 1991, Miami, Fla.

[52] JONES, R. W., and M. DEMARIA, 1991: A variational method for including persistence in a hurricane track forecast model. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[53] KAPLAN, J., and J. L. FRANKLIN, 1991: The relationship between the motion of Tropical Storm Florence (1988) and its enviromental flow. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[54] MARKS, F. D., JR., and R. A. Houze, Jr., 1991: Comparison of the kinematic structure of an intensifying and a weakening hurricane: Hurricanes Emily (1987) and Norbert (1984). *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[55] OOYAMA, K. V., 1990: A dynamic test of diagnostic pressure calculation. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[56] POWELL, M. D., 1990: Meteorology subsection. Post-Disaster Study Team Report on Hurricane Hugo in the Carolinas. National Academy Press, Washington, D.C.

[57] POWELL, M. D., 1991: Observations of boundary layer structure and mesoscale wind fields in a midlatitude marine rainband during GALE. *1st International Winter Storm Symposium*–AMS, Jan. 13–18, 1991, New Orleans, La.

[58] POWELL, M. D., 1991: Surface wind distribution of Hurricane Hugo in the Carolinas. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*–AMS, May 6–10, 1991, Miami, Fla.

[59] POWELL, M. D., and P. G. BLACK, 1990: The relationship of hurricane reconnaissance flight-level wind measurements to winds measured by NOAA's oceanic platforms. *J. Wind Engineer. and Industrial Aerodyn.*

[60] POWELL, M. D., P. P. DODGE and M. L. BLACK: The landfall of Hurricane Hugo in the Carolinas. *Wea. Forecasting.*

[61] ROSENTHAL, S. L., 1991: A history of research at the NOAA Hurricane Research Division, including interactions with F.S.U.'s Department of Meteorology. *40th Anniversary Volume*, Department of Meteorology, Florida State University, Tallahassee, Fla.

[62] SHAPIRO, L. J., 1991: The effect of vertical wind shear on hurricane motion in a three-layer model. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[63] WILLIS, P. T., and J. Hallett, 1990: Microphysical measurements from an aircraft ascending with a growing isolated maritime cumulus tower. *J. Atmos. Sci.*, 47.

[64] WILLIS, P. T., and A. J. Heymsfield, 1991: Trajectories of hydrometeors in Hurricane Emily. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

[65] WILLOUGHBY, H. E., 1991: Semispectral models of moving hurricane-like vortices. *Ex. Abst., 19th Conf. on Hurricanes and Tropical Meteorology*-AMS, May 6-10, 1991, Miami, Fla.

A.3 Submitted

[66] BLACK, P. G., G. Holland and M. D. POWELL, 1991: Boundary layer dynamics in Hurricane Kerry (1979): Part II - Heat and moisture budgets. *J. Atmos. Sci.*

[67] Giese, G. S., P. G. BLACK, D. C. Chapman and J. A. Fornshell: Causation of large-amplitude coastal seiches on the Caribbean coast of Puerto Rico. *J. Phys. Oceanog.*

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

[69] Houze, R. A., Jr., F. D. MARKS, JR. and R. A. BLACK: Dual-aircraft investigation of the inner core of Hurricane Norbert: Part II, Mesoscale distribution of ice particles. *J. Atmos. Sci.*

[70] 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 structure. *J. Atmos. Sci.*

[71] WILLOUGHBY, H. E.: Reply. (Addressed to W. Gray re. "Gradient Balance in Tropical Cyclones," by H. E. Willoughby.) *J. Atmos. Sci.*

A.4 In Preparation

[72] BLACK, M., and H. WILLOUGHBY: Concentric eyewalls of Hurricane Gilbert. *Wea. Forecasting.*

[73] BLACK, P. G.: Ocean response to tropical cyclones, I: Sea surface temperature patterns induced by fast-moving storms. *J. Phys. Oceanog.*

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

[75] BURPEE, R. W., P. P. DODGE, F. D. MARKS, JR. and M. L. BLACK: Land-based radar observations of the convective-scale and mesoscale structure of hurricane rainbands. *Mon. Weather Rev.*

[76] DODGE, P. P.: Rainbands and the Gulf Stream during the GALE field program. *Mon. Weather Rev.*

[77] GAMACHE, J. F., R. A. Houze, Jr. and F. D. MARKS, JR.: Dual-aircraft investigation of the inner core of Hurricane Norbert: Part III, Water budget. *J. Atmos. Sci.*

[78] POWELL, M. D.: Meteorological aspects of wind damage. In *Manual of Wind Damage Investigation*. ASCE Task Committee on Wind Damage Investigation. American Society of Civil Engineers.

[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] POWELL, M. D., P. P. DODGE and M. BLACK: The landfall of Hurricane Hugo in the Carolinas. *Wea. Forecasting.*

[81] Tanner, A. B., P. G. BLACK, C. T. Swift and K. St. Germain: Surface wind speed and rain rate estimation in hurricanes using airborne microwave spectral radiometer measurements. *J. Atmos. Oceanic Tech.*

Appendix B: Presentations

B.1 AOML Seminars Presented by Visitors to HRD

1989

November 16	Dr. Carl Friehe (University of California at Irvine): "Surface-Layer Turbulence Around a Sea Surface Temperature Front: Measurements From Two Turbulence Aircraft"
December 13	Dr. David Atlas (NASA/Goddard): "The Estimation of Convective Rainfall by Area Integrals and Height: An Update and Synthesis" (CIMAS Seminar Series)
December 14	Dr. David Atlas (NASA/Goddard): "Climatologically Tuned Reflectivity/Rain-Rate Relations" (CIMAS Seminar Series)

1990

January 8	Dr. Stephen J. Lord (National Meteorological Center): "Confessions of a Neophyte Hurricane Bog(us)eyman"
January 29	Dr. Kerry Emanuel (Massachusetts Institute of Technology): "Negative Influences on Axisymmetric Tropical Cyclogenesis" (CIMAS Seminar Series)
February 12	Dr. Robert A. Houze, Jr. (University of Washington): "The Equatorial Mesoscale Experiment (EMEX): An Overview and Preliminary Results"
February 13	Dr. Calvin T. Swift (University of Massachusetts): "Design and Performance of an Airborne C-Band Scatterometer to Measure the Ocean Surface Wind Vector"
February 21	Dr. John R. Gyakum (McGill University): "A Diagnostic Study of Cyclogenesis in the Western North Pacific Ocean" (CIMAS Seminar Series)
February 22	Dr. John R. Gyakum (McGill University): "Antecedent Meteorological Conditioning Associated With Explosive Surface Cyclogenesis" (CIMAS Seminar Series)
March 7	Mr. Mark D. Handel (Massachusetts Institute of Technology): "Tropical Cyclone Intensification From Finite Amplitude Disturbances" (CIMAS Seminar Series)
March 9	Mr. Mark D. Handel (Massachusetts Institute of Technology): "Greenhouse Science History From Explanation to Prediction" (CIMAS Seminar Series)
June 14	Dr. Georgi Sutyrin (USSR Academy of Sciences) "Prediction of Intense Vortex Motion" (CIMAS Seminar Series)
June 15	Dr. Georgi Sutyrin (USSR Academy of Sciences) "Coupled Model of Ocean Respopnse to a Hurricane, Including a Case of Eddy Generation by a Stationary Hurricane" (CIMAS Seminar Series)
July 16	Dr. John Molinari (State University of New York at Albany) "Enviromental Interactions and Hurricane Intensity Change"
July 18	Dr. Frank Roux (Centre de Recherches en Physique de l'Environnement) "Thermodynamic Retrieval From Doppler Radar Data in a West African Squall Line, a Narrow Cold Frontal Rainband, and Hurricane Norbert" (CIMAS Seminar Series)
August 1	Dr. Jong-Jin Baik (North Carolina State University) "Intense Mesoscale Vortices Developed and Maintained by Vortex-Ocean Interaction" (CIMAS Seminar Series)

B.2 AOML Informal Research Reports Presented by HRD Staff

1989

November 14	Dr. HUGH E. WILLOUGHBY: "The Art and Science of Hurricane Tracking"

1990

January 23	Dr. MARK DEMARIA: "Near Real-Time VICBAR Hurricane Track Forecast Results for 1989"
January 30	Dr. MARK D. POWELL: "The Wind Field of Hurricane Hugo at Landfall"
February 23	Dr. ROBERT W. JONES: "Progress in Data Assimilation With a Barotropic Model"
March 6	Mr. PAUL T. WILLIS: (1) "Oceanic Cumuli"; (2) "Melting Layers"; (3) "Hurricane Frequency -- QBO and the Eye"
March 15	Dr. FRANK D. MARKS, JR.: "Kinematic structure of Hurricane Emily as Determined by Airborne Doppler Radar"
April 3	Dr. KATSUYUKI V. OOYAMA: "More About the Moist Thermodynamics in the Primitive Form"
April 5	Dr. JOHN F. GAMACHE: "The Water Budget of Hurricane Norbert"
April 26	Mr. JAMES L. FRANKLIN: "Recent Diagnostic Results From HRD Synoptic-Flow Experiments"
May 22	Mr. ROBERT A. BLACK: "Electrical and Microphysical Studies in Hurricanes"
May 29	Dr. PETER G. BLACK: "Unexpected Mesoscale Features in Hurricanes: A Comparison of Hugo and Friends"
June 7	Dr. ROBERT W. BURPEE: "Tropical Depression 2 of 1987: A Second Look at the Surface Winds"
June 19	Dr. LLOYD J. SHAPIRO: "The 30-60 Day Oscillation in the Atlantic"

B.3 HRD Informal Research Reports

1990

April 9	Mr. VICTOR WIGGERT: "What's to Worry About a Little Water? Storm Surge!"
April 16	Mr. SIM D. ABERSON: "The Effect of Wisconsin Cloud Motion Vectors on VICBAR Forecasts"
April 23	Mr. PETER P. DODGE: (a) "Some Airborne Radar Geometry"; (b) "GALE Rainband Environments"
May 21	Mr. JOHN KAPLAN: "Statistical Intensity Prediction of Tropical Cyclones: Some Preliminary Results"
May 23	Mr. MICHAEL L. BLACK: "Vertical Motions in Tropical Cyclones as Determined From Airborne Doppler Radar"

B.4 Presentations Given Outside by HRD Staff

1989

October 19	Drs. PETER G. BLACK and FRANK D. MARKS, JR: "Encounter With an Intense Mesoscale Vortex in Hurricane Hugo (15 September 1989)" (at NOAA/Aircraft Operations Center, Miami, Fla.)
November 9	Dr. PETER G. BLACK: "Mesoscale Ocean Response to Tropical Cyclones" (at Stennis Space Center, Bay St. Louis, Miss.)
November 28	Dr. MARK D. POWELL: "Meteorological, Engineering, Sociological, and Preparedness Events Surrounding Hurricane Hugo" (at Congressional Briefing on Hurricane Hugo, Washington, D.C.)
November 29	Dr. MARK D. POWELL: "Characteristics of the Hurricane Planetary Boundary Layer" (at Florida State University)
November 30	Dr. STANLEY L. ROSENTHAL: "FSU'S Department of Meteorology and NOAA's Hurricane Research Division: Interwoven for More Than 30 Years" (at Florida State University)

1990

January 4	Dr. MARK DEMARIA: "An Overview of Hurricane Track Prediction" (at NOAA/National Severe Storms Laboratory, Norman, Oklahoma)
March 22	Dr. HUGH E. WILLOUGHBY: "Convective Rings and Concentric Eyewalls" (at National Hurricane Center, Miami, Fla.)
April 4	Dr. PETER G. BLACK: "Observations of an Intense Mesoscale Vortex Within Hurricane Hugo" (at the Civil Aviation Authority, Moscow, U.S.S.R.)
April 18	Dr. LLOYD J. SHAPIRO: "Hurricane Evolution in Simple Models" (at the University of Illinois)

Presentations Given Outside by HRD Staff (Continued)

April 20	Dr. FRANK D. MARKS, JR.: "Close Encounters of the Fourth Kind" (at Massachusetts Institute of Technology)
May 24	Dr. PETER G. BLACK: "Ocean Response to Hurricanes" (at Massachusetts Institute of Technology)
May 27	Dr. JOHN F. GAMACHE: "The Water Budget of Hurricane Norbert (1984)" (at the University of Washington)
June 18	Dr. MARK D. POWELL: "Boundary Layer Structure Dynamics in Outer Hurricane Rainbands" (at the National Center for Atmospheric Research, Boulder, Colo.)
June 22	Dr. MARK DEMARIA: "Real-Time Track Forecasts With a Nested Hurricane Model" (at Colorado State University)
August 2	Dr. HUGH E. WILLOUGHBY: "Development of Hurricane Hugo" (at National Hurricane Center, Miami, Fla.)
August 2	Dr. MARK D. POWELL: "Development of a Real-Time Surface Wind Analysis Package" (at National Hurricane Center, Miami, Fla.)
August 2	Dr. PETER G. BLACK: "A Surface Wind Estimation Worksheet" (at National Hurricane Center, Miami, Fla.)
August 2	Mr. SIM D. ABERSON: "VICBAR" (at National Hurricane Center, Miami, Fla.)
August 2	Mr. JAMES L. FRANKLIN: "Using ODW's to Determine the Optimum Steering Level for VICBAR Forecasts" (at National Hurricane Center, Miami, Fla.)
August 2	Dr. MARK DEMARIA: "Development of a Statistical Hurricane Intensity Prediction Scheme (SHIPS)" (at National Hurricane Center, Miami, Fla.)
August 2	Dr. ROBERT W. BURPEE: "Improvements in Airborne Analysis of Observations That Support Operational Hurricane Forecasting" (at National Hurricane Center, Miami, Fla.)
August 9	Dr. HUGH E. WILLOUGHBY: "Jet Aircraft Operations in Hurricanes and Typhoons" (at NASA/Ames Research Center, San Francisco, Calif.)

B.5 Special Presentations

AOML/CIMAS Program Review

May 16, 1990, Miami, Florida

Dr. STANLEY L. ROSENTHAL	"Introduction to the Hurricane Research Division"
Dr. ROBERT W. BURPEE	"Omega Dropwindsonde (ODW) Observations of the Environmental Flow Around Hurricanes"
Dr. MARK DEMARIA	"Real-Time Tests of a Nested Hurricane Track Forecast Model"
Dr. HUGH E. WILLOUGHBY	"Concurrent Analyses of Hurricane Gilbert from Maximum Intensity to Final Landfall"

Special Presentations (Continued)

Dr. PETER G. BLACK	"Estimation of Surface Winds for Hurricane Forecasts and Warnings"
Dr. MARK D. POWELL	"Surface Wind Fields of Hurricane Hugo in the Carolinas"
Dr. FRANK D. MARKS, JR.	"Airborne Doppler Radar Impacts on Hurricane Research"
Dr. LLOYD J. SHAPIRO	"Tropical Atlantic Climatic Fluctuations and Hurricane Cycles"

B.6 Unpublished[4] Conference Presentations

26th Annual NOAA/NWS Hurricane Conference

November 14-16, 1990, Coral Gables, Florida

Discussion topic:	"ASDL Data Acquisition and Format"
Sponsors:	Drs. ROBERT W. BURPEE and HUGH E. WILLOUGHBY

44th Annual Interdepartmental Hurricane Conference

Research Committee Meeting - January 9, 1990

Homestead AFB, Florida

Mr. SIM D. ABERSON and Dr. MARK DEMARIA	"Analyses and Track Forecasting of Hurricane Hugo"
Dr. PETER G. BLACK	"Some Differences Between Surface and Flight-Level Wind Measurements in Recent Hurricanes"
Dr. PETER G. BLACK and Dr. FRANK D. MARKS, JR.	"Aircraft Penetration of a Hurricane 'Suction Vortex' in Hurricane Hugo (September 15, 1989)"
Dr. MARK DEMARIA and Mr. SIM D. ABERSON	"Verification of a Nested Hurricane Track Forecast Model (VICBAR) for the 1989 Atlantic Hurricane Season"
Dr. HUGH E. WILLOUGHBY, Mr. WILLIAM P. BARRY, and Mr. M. EDWARD RAHN	"Real-Time Aircraft Observation of Hurricanes in 1989"

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

Unpublished Conference Presentations (Continued)

Six Months After Hurricane Hugo - Preliminary Findings-NSF,

University of Puerto Rico, March 12, 1990, Mayaguez, P.R.

Dr. MARK D. POWELL "Hurricane Hugo in the Carolinas"

Colloquium: On Tropical Meteorology and the

Study of Hurricanes, April 3, 1990, Moscow, U.S.S.R.

Dr. PETER G. BLACK "Observations of an Intense Mesoscale Vortex Within Hurricane Hugo"

Dr. PETER G. BLACK "Ocean Response Observations in the Wake of Hurricane Gilbert"

B.7 Workshop Participation

Dr. FRANK D. MARKS, JR.
Tropical Ocean/Global Atmosphere Research Program Coupled Ocean-Atmosphere Response Experiment Workshop-NCAR, October 5-6, 1989, Boulder, Colorado

Mr. PAUL T. WILLIS
STORM Workshop, October 25-27, 1989, Champaign, Illinois

Dr. PETER G. BLACK
"Vertical/Horizontal Boundary Layer Structure Over the Ocean." WMO Second International Workshop on Tropical Cyclones, November 27-December 8, 1989, Manila, Philippines

Dr. ROBERT W. BURPEE
Aircraft and Airborne Instrumentation Workshop, February 7-9, 1990, Boulder, Colorado

Dr. ROBERT W. BURPEE
NOAA Technical Exchange Conference, February 26-27, 1990, Columbia, Maryland

Dr. MARK D. POWELL
Workshop on Hurricane Hugo-University of Florida, May 20-22, 1990, Folly Beach, South Carolina

Dr. KATSUYUKI V. OOYAMA
Workshop on Comparison of Numerical Methods for Solving Nonlinear Flows-University of Illinois, September 10-13, 1990, Champaign, Illinois

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
Dr. MARK DEMARIA	Chairman, Miami Chapter, American Meteorological Society
	Member, Ad-Hoc Group for Tropical Cyclone Research, Federal Coordinator for Meteorological Services and Supporting 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
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
Dr. KATSUYUKI V. OOYAMA	Fellow, American Meteorological Society
Dr. MARK D. POWELL	Member, National Research Council, Natural Disaster Investigation Team
	Chairman, Meteorological Subcommittee, American Society of Civil Engineers Task Committee on Wind Damage Investigation
	Chairman, Research Committee, 44th 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
	Member, ERL Forecast Systems Laboratory Advisory Committee

Committee Memberships (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
Mr. PAUL T. WILLIS	Member, Cloud Physics Panel, National STORM (STormscale Operational and Research Meteorology) Program

C.2 CIMAS Visiting Scientists

Dr. David Atlas, Visiting Fellow

Affiliation:	National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, Maryland
Research Area:	Confirmation of an algorithm which relates the area-average rain rate from a number of storms to the fractional area covered by precipitation exceeding a prescribed threshold, the latter being set by radar.
HRD Co-Investigator:	Dr. FRANK D. MARKS, JR.

Dr. Frank Roux, Senior Research Associate

Affiliation:	Centre de Recherches en Physique de l'Environnement Terrestre et Planetaire, Issy-Les-Moulineaux, France
Research Area:	Airborne Doppler radar applications and analysis techniques
HRD Co-Investigators:	Drs. JOHN F. GAMACHE and FRANK D. MARKS, JR.

Dr. Jong-Jin Baik, Research Associate

Affiliation:	North Carolina State University
Research Area:	Analysis of hurricane momentum budgets for a statistically based hurricane intensity forecast model
HRD Co-Investigator:	Dr. MARK DEMARIA

C.3 Students at HRD

Mr. Chris Landsea

Affiliation:	Colorado State University
Research Area:	Real-time analysis of aircraft observations
Assisting:	Dr. HUGH E. WILLOUGHBY

Mr. Jeffrey Meyers

Affiliation:	Columbia University
Research Area:	Hurricane intensity change
Assisting:	Dr. MARK DEMARIA

C.4 Visitors

Dr. David Atlas, NASA/Goddard, Greenbelt, Maryland
Dr. Howard Bluestein, University of Oklahoma
Dr. William R. Cotton, Colorado State University
Mr. Jed Decory, T. V. Ontario, Canada
Dr. Kerry Emanuel, Massachusetts Institute of Technology
Dr. Carl Friehe, University of California at Irvine
Mr. Glenn Garte, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.
Dr. John Gyakum, McGill University, Canada
Dr. John Hallett, University of Nevada
Mr. Mark D. Handel, Massachusetts Institute of Technology
Dr. Robert A. Houze, Jr., University of Washington
Mr. Ted Hudson, UNISYS Corporation
Dr. Chester Jelesnianski (NWS/Techniques Development Laboratory, Silver Spring, Md.)
Mr. Michael Kinney, T. V. Ontario, Canada
Dr. John Knauss, NOAA, Washington, D.C.
Dr. Stephen J. Lord, NOAA/National Meteorological Center, Washington, D.C.
Dr. Robert McIntosh, University of Massachusetts/Amherst
Mr. Dennis Miller, Massachusetts Institute of Technology
Dr. John Molinari, University of New York at Albany
Dr. Ned Ostenso, NOAA, Washington, D.C.
Dr. Xiang-Han Pan, Institute for Atmospheric Research, Beijing
Dr. G. W. Qiu, Institute for Atmospheric Research, Beijing
Mr. Arthur Rolle, Bahamas Meteorological Service
Dr. Clive Saunders, University of Manchester Institute of Science and Technology
Ms. Karen St. Germain, University of Massachusetts
Dr. Georgi Sutyrin, U.S.S.R. Academy of Sciences
Dr. Calvin Swift, University of Massachusetts/Amherst
Dr. Edward Wash, NOAA/Wave Propagation Laboratory, Boulder, Colo.
Dr. Henry Yao, National Academy of Sciences, New York
Dr. Wei-Yiang Zheng, Institute for Atmospheric Research, Beijing
Dr. Xiuem Zhou, Institute for Atmospheric Research, Beijing

C.5 HRD Staff on September 30, 1990

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

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
Feuer, Steven E.	Meteorologist
Franklin, James L.	Meteorologist
Friedman, Howard A.	Meteorologist
Gamache, John F.	Meteorologist
Goldenberg, Stanley B.	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
Morrissey, Barbara J.	Computer Operator
Ooyama, Katsuyuki V.	Meteorologist
Powell, Mark D.	Meteorologist
Putland, Gerald E.	Physical Scientist
Rahn, M. 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
ASCE	American Society of Civil Engineers
ASDL	aircraft-satellite data link
CAI	computer-assisted instruction
CALM	cognitive and affective learning model
CIMAS	Cooperative Institute for Marine and Atmospheric Science
CLASS	Cross-Chain Loran-C Atmospheric Sounding System
CLIPER	climatology/persistence
DMSP	Defense Meteorological Satellite Program
DRI	Desert Research Institute
ECMWF	European Centre for Medium Range Weather Forecasts
EMEX	Equatorial Mesoscale Experiment
EOF	empirical orthogonal function
EPOCS	Equatorial Pacific Ocean Climate Studies
FAST	forward and aft scanning technique
FSU	Florida State University
GALE	Genesis of Atlantic Lows Experiment
GATE	GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GOES	Geostationary Operational Environmental Satellite
HART	height-area rainfall technique
HBL	hurricane boundary layer
HRD	Hurricane Research Division
IAMAP-ICCP	International Association of Meteorology and Atmospheric Physics-International Commission on Cloud Physics
JW	Johnson-Williams
McIDAS	Man-Computer Interactive Data System
MCS	mesoscale convective system
MIT	Massachusetts Institute of Technology
MSL	mean sea level
NCAR	National Center for Atmospheric Research
NGM	nested grid model
NHC	National Hurricane Center
NMC	National Meteorological Center
NSF	National Science Foundation

NSSL	National Severe Storms Laboratory
NWS	National Weather Service
ODW	Omega dropwindsonde
OLR	outgoing longwave radiation
QVADIS	general-purpose base model
RAM	relative angular momentum
SAFER	spectral application of finite element representation
SCAAL	storm-centered analysis algorithm
SFMR	Stepped-Frequency Microwave Radiometer
SHIPS	statistical hurricane intensity prediction scheme
SLOSH	sea, lake, and overland surge from hurricanes
SSM/I	Special Sensor Microwave/Imager
SST	sea surface temperature
STORM	STormscale Operational and Research Meteorology
TOGA COARE	Tropical Oceans Global Atmospheres Coupled Ocean-Atmosphere Response Experiment
TRMM	Tropical Measuring Rainfall Mission
UMIST	University of Manchester Institute of Science and Technology
UW	University of Washington
VAS	VISSR Atmospheric Sounder
VICBAR	barotropic hurricane track prediction model
VISSR	Visible and Infrared Spin-Scan Radiometer
WOTAN	Weather Observation Through Ambient Noise
WMO	World Meteorological Organization
WR	western rainbands