Hurricane Rainband and Intensity Experiment 2005: RAINEX

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PROJECT OVERVIEW

Abstract

The Hurricane Rainband and Intensity Experiment (RAINEX) joins with several other programs in 2005 to focus on the intensity changes of mature hurricanes in relation to interactions between the rainbands and inner-core (eyewall) region. RAINEX will build on the flight program of the NOAA Hurricane Research Division (HRD) supplemented by the NRL P3 equipped with the NCAR Eldora radar to obtain Doppler radar and dropsonde data simultaneously in the rainband and eyewall regions. Previous studies have tended to emphasize either the inner core region or rainbands but little has been done on their simultaneous dynamics and interactions. The Doppler radar and dropsondes will be used in coordination with the University of Miami's high-resolution coupled ocean-atmosphere version of the MM5 mesoscale model. Model simulations of recent Hurricanes Fabian (2003) and Isabel (2003) will guide the design of the flight program. In near real time, the model observations will be used to assess the success of the flights and to help make modifications to the flight program to maximize the chance of successful flights. In post-analysis, the aircraft data will be compared to the model output to determine the accuracy of the model simulations and the model will be used to extend the diagnosis possible from the data alone.

RAINEX is part of a larger program, which will be coordinated by HRD. TEXMEX II has been proposed for the Pacific off the coast of Mexico, and will include early identification and tracking of hurricanes. TEXMEX II thus complements RAINEX, which emphasizes the mid-later stages of mature storms threatening the U.S. from the Atlantic. Finally, the NASA program (CAMEX 5) will provide a set of higher altitude aircraft measurements, including cloud physics and remote sensing, which will supplement some of the storms investigated in RAINEX and CAMEX 5.

1. Scientific Background

Over the last a few decades forecasts of hurricane tracks have improved significantly, largely as a result of improvement of large-scale numerical forecast models and satellite observations, whereas relatively little progress has been made in forecasts of hurricane intensity. This was clearly evident in recent numerical model predictions of Hurricane Lili (2002). None of the current numerical model guidance captured the rapid intensification or the rapid decay before the landfall of Hurricane Lili in the Gulf of Mexico (NOAA/TPC/NHC report). The lack of success in intensity forecasting may be attributed to insufficient spatial resolution to resolve the hurricane inner core (e.g., eye and eyewall) and rainband structures and inadequate representation of physical processes in hurricane prediction models. Although the maximum potential intensity (MPI) of hurricanes can be estimated from the sea surface temperature and upper tropospheric temperature and humidity (Emanuel 1987, 1988; Evans 1993; DeMaria and Kaplan 1994; Holland, 1997), most hurricanes never reach their MPI. Observations have shown that intensity changes are often associated with evolution of the storm structure and complex interactions with aspects of the storm environment, such as vertical shear (e.g., Elsberry and Jeffries 1996; DeMaria 1996; Frank and Ritchie 1999), mean flow (e.g., Tuleya and Kurihara 1981; Peng et al. 1999), and low-to-mid-level dry air (e.g., Dunion and Velden 2002).

Most hurricanes exhibit an eyewall and a set of outer spiral rainbands (Willoughby et al. 1984). The outer rainbands are the spiral-shaped patterns of precipitation that were seen in the earliest radar observations of tropical cyclones. These bands are typically 5-50 km wide and 100-300 km long, and they are ubiquitous in tropical cyclones. They are observed to have a complex three-dimensional structure with extensive stratiform rain areas imbedded with deep convective cores (e.g., Atlas et al. 1963, Barnes et al. 1983; Barnes et al. 1991). Some very intense hurricanes exhibit concentric eyewalls, and in these storms intensity changes have been observed to occur in connection with an eyewall contraction and replacement cycle (Willoughby et al. 1982; Black and Willoughby 1992). A secondary wind maximum is sometime observed to be associated with the outer rainbands (Samsury and Zipser 1995).

Willoughby et al. (1984) described a frequently observed spiral rainband structure, namely the stationary band complex (SBC), which includes a principal band, a connecting band linking the inner eyewall and outer rainband, and occasionally a secondary rainband between the eyewall and the outer principal rainband (see Fig. 18 of Willoughby et al. 1984). The SBC is located near the inner core of weak tropical cyclones and relatively far away from the center of the intense hurricanes. In some intense hurricanes, the principal bands do not join the eyewall; rather they leave a clear moat around the eyewall (Willoughby et al., 1982). They may subsequently become concentric and form a secondary eyewall, which then monopolizes moist energy and partially blocks moist radial inflow to the inner eyewall. The inner eyewall collapses, leading to an eyewall replacement cycle during which storm intensity changes rapidly.

The rainband patterns that are observed to relate to intensity changes may be simplified and summarized into four stages (Figure 1):

i. Cyclonic inward spiral rainbands commonly observed in almost all tropical cyclones.
ii. Enclosed convective ring at the storm center with a principal band as the storm intensifies. The (downshear) tail of the principal band tends to be more convective, while the (upshear) end of the principal band, near where it connects to the eyewall tends to be stratiform. In the sketch the storm would be moving toward the northwest.
iii. Concentric eyewalls (including the primary eyewall and secondary wind maximum) that sometimes lead to further intensification as the primary eyewall contracts.

iv. Breakdown of the primary eyewall and eyewall replacement leading to a weakening of storm intensity.

Not all storms look like the idealization in Figure 1. Nor do all storms experience all four of the life stages (i-iv). The first two stages are commonly observed in most tropical cyclones, and the last two frequently occur in intense hurricanes. Regardless of the configuration in time and space, a consistent dynamical distinction exists between convective bands that spiral outward from the center and convective rings that encircle the center. The proposed study recognizes that intensity changes of the hurricane appear to be related to the interactions of the two types of bands and to the manner in which the spiral convective bands evolve into primary or secondary eyewalls.

The hurricane inner-core region has been studied extensively in observational studies. Numerous aircraft observations have documented the eyewall region, including concentric eyewall cases (Willoughby et al. 1982; Jorgensen 1984a, b; Jorgensen et al. 1985; Marks and Houze 1984, 1987; Willoughby 1990; Marks et al. 1992; Houze et al. 1992; Gamache et al. 1993; Black and Willoughby 1992, Reasor et al. 2000). Observational studies have also explored rainbands (Barnes et al. 1983; Barnes and Stossmeister 1986; Powell 1990a, b; Samsury and Zipser 1995). These studies draw some limited conclusions regarding the interactions of the outer rainbands with the inner core dynamics. For example, the results of Barnes et al. (1983) and Powell (1990a, b) suggest that the rainband downdrafts can sometimes lower the low-level θ_e of air approaching the eyewall. However, there is a general dearth of observations including how the hurricane outer rainbands interact with storm's inner core, and hence with storm intensity changes.

Some idealized modeling studies have attempted to explain the existence of the rainbands. Kurihara (1976) and Willoughby (1978) proposed that internal gravity-inertia waves are responsible for the outward propagating spiral rainbands. Others have attributed the boundary-layer asymmetry as a possible cause (e.g., Shapiro 1983). More recently, Guinn and Schubert (1993), using an f-plane shallow-water model, conducted a series numerical experiments and concluded that the hurricane rainbands can be explained by the potential vorticity (PV) redistribution or PV wave breaking and vortex merging processes. Montgomery and Kallenbach (1997) later extended the early work and developed the framework for 2-D phase and group velocities for vortex-Rossby waves. They described the outward propagation of rainbands as vortex Rossby waves. A recent study by Chen and Yau (2001) using the nonhydrostatic, full physics MM5 has confirmed that the rainbands simulated in the model are vortex-Rossby waves.

Theoretical and modeling studies have identified number of mechanisms that may be responsible for structure and intensity changes in the inner-cores of tropical cyclones. Extending Eliassen's (1951) theory for simple balanced vortices to tropical cyclones, Shapiro and Willoughby (1982) showed how eyewall heating leads to low-level wind intensification, warming in the eye and lower surface pressures. Emanuel (1997) pointed out that these lower surface pressures also have an important and positive thermodynamic feedback on the storm. Asymmetric forcing has also been studied as a possibly important intensification mechanism, whereby asymmetries in the wind field cause inward fluxes of angular momentum as they are sheared by the symmetric flow (Pfeffer 1958; Carr and Williams 1989; Challa et al. 1998). At periods of high storm intensity, these vortex-Rossby waves can become unstable, leading to polygonal eyewalls (Muramatsu, 1986), mesovortices (Black and Marks 1991), and even a complete breakdown and rearrangement of the inner-core structure (Schubert et al., 1999; Nolan and Montgomery 2002), which has been observed directly (Knaff et al., 2002, Kossin and Easting, 2001). Secondary eyewall formation and eyewall replacement cycles are another dynamical process of great interest (Willoughby et al., 1992). While secondary wind maxima are another potential source of dynamic instability, Kossin et al. (2000) showed that the outer ring can be stabilized by the strong radial shear of the azimuthal wind associated with the inner-core vortex. Mechanisms for the formation of secondary wind maxima and eyewalls remain under investigation.

A central concept in understanding symmetric and asymmetric hurricane dynamics is the conservation of PV and its utility as a predictor of the surrounding flow under balanced or "quasi-balanced" dynamics (Shapiro and Montgomery, 1993). Thus observations of PV, and its redistribution via diabatic heating, are critical to understanding how inner-core asymmetries, spiral bands, and secondary eyewalls cause intensity and structure change. Using a vertical wind profiler, May and Holland (1999) estimated PV production in rainband stratiform rain regions, and suggested that such PV anomalies contribute to intensification as they spiral into vortex core. The shearing deformation can stretch the vorticity into filaments that spiral toward the center of the tropical cyclone (e.g., Holland and Dietachmayer 1993). In an idealized numerical simulation of tropical cyclone, Wang (2002) found that inward intruding outer rainbands interact with the eyewall circulation and may occasionally cause weakening of the storm intensity. Using a three-dimensional, nonhydrostatic model with fully "unbalanced" dynamics, Nolan and Grasso (2003) have simulated the hydrostatic and gradient wind adjustment process by which heating anomalies generate balanced PV anomalies. Their results show that that the PV structures caused by asymmetric heating are quite different from those used in previous studies, and that whether asymmetric heating leads to intensification depends critically on these PV structures. Therefore, direct measurement of the wind, temperature, and thus PV fields in the vicinity of asymmetric convection and spiral bands is critical to resolving the role of asymmetric convection in intensity change.

Most of these previous studies used either simple models that did not contain moisture or idealized vortices and as such were unable to explicitly predict rainband convection and precipitation. Consequently, aspects of their formation, dynamics, and interaction with the hurricane primary vortex are still unresolved.

Samsury and Zipser (1995) analyzed data from 173 radial legs thought to be associated with convectively-active outer rainbands. They found that about 30% of the outer rainbands in their sample contained a secondary horizontal wind maximum (SHWM), similar to the eyewall. Samsury and Zipser's (1995) cases were limited to flight-level data and horizontal maps of reflectivity from the lower fuselage radar. It is our premise that extensive dual-Doppler data from multiple aircraft and dropwindsondes on the same aircraft missions can add substantially to the knowledge of the structure and evolution of the outer rainbands and concentric eyewalls. Such intensive coverage by dual-Doppler winds and soundings will moreover be a vastly superior comparison data set for modeling than any pre-existing data sets.

RAINEX (the Hurricane Rainband ANd INtensity EXperiment) aims to provide precisely such a data set by using airborne Doppler radar *both* near the eyewall *and* in the outer rainband region of hurricanes. The proposed research will also carry out numerical model experiments to interpret the observations obtained by aircraft and provide physical insights on rainbands and vortex mean flow interaction. The SBC and *principal band* identified by Willoughby et al. (1984) appear to be key dynamic elements and are readily identified in real time by airborne radar. The features are persistent and therefore amenable to performing aircraft penetrations of them, as directed by scientists on the aircraft. The data collected can be organized relative to a composite storm with a characteristic SBC and principal band. If the principal band involves a SHWM it would have the necessary ingredients to form a secondary eyewall if its inner end wrapped around the storm center. By real time identification and targeted probing of these features by multiple dual-Doppler aircraft, we will obtain data that will constrain model simulations of the rainband/inner-core interactions. Our proposed experimental and modeling study will in this way focus on the principal band and other major rainbands close to the inner core region and their dynamic connection with the inner core region of the storm.

2. Working hypothesis and objectives

The vertical distribution of heating is different in convective and stratiform regions (Houze 1982; 1989; Mapes and Houze 1995; Houze 1997). The deep convective cores produce PV in a deep layer and maximum heating in the low-to-mid troposphere, whereas the PV is confined to the mid-troposphere with a maximum heating in the upper troposphere in stratiform rain area. The experience of airborne scientists on hurricane flights has been to notice that radar observations tend to show rainbands having more deep convective cores on the downshear (upwind) side of the storm, whereas stratiform precipitation dominates in the upshear (downwind) part of the storm. This impression constitutes an important empirical working hypothesis. A bias toward convective structure on the downshear side versus stratiform structure on the upshear side would produce asymmetric heating and PV profiles around the storm. We would expect this asymmetry to affect the vortex dynamics and storm intensity. In this study we will measure this heating asymmetry and determine how it affects the interaction between the rainbands and hurricane mean vortex.

Hurricane rainbands are the major source of heating outside of the hurricane eyewall region. Convectively induced PV in the rainbands can be stretched into filaments that spiral inward along the bands toward the storm center. This process may increase PV in the inner core region when the rainbands evolve into the SBC structure with a principal band (Willoughby et al. 1984, also see Figure 1, stage ii). The SBC represents a relatively steady and stationary source of diabatic heating and PV production near the RMW. Studies by Hack and Schubert (1986), Chen and Frank (1993), and Nolan and Grasso (2003) indicate that the intensification caused by such heating increases dramatically as air moves closer to the center of the storm. However, the vertical structure of the heating pattern around the storm is not known. Modeling studies of Chen and Frank (1993) and Bister and Emanuel (1997) have suggested that the stratiform rain in the storm center is favorable for intensification of the vortex. The vertical structure of the heating will be addressed in the research proposed here. We expect that that the heating will have a vertical structure of a more convective type farther from the storm in the tail of the principal band and of a more stratiform type in the part of the principal band that is close to and making contact with the eyewall, as indicated in Figure 1, stage ii.

Outside the hurricane inner core, PV is "axisymmetrized" by the shear of the symmetric vortex and may ultimately contribute further to intensification via the wave-mean flow interactions of associated vortex-Rossby waves (Montgomery and Kallenbach, 1997). Through this process, PV perturbations in rainbands can change the symmetric PV fields and thus the mean vortex itself. Since the vertical distribution of the heating (and hence the PV generation) in a rainband may depend on the rainband's structure and location relative to the hurricane center, as noted above, the vertical structure of the PV being axisymmetrized will be a function of the position of the rainband relative to the storm. By documenting the convective vs. stratiform structure of rainbands in various positions relative to the storm center, we will indicate the nature of the PV anomalies being axisymmetrized at different radii and azimuths from relative to the storm center.

The proposed study will determine the asymmetry of the heating by using airborne Doppler radar to map the convective and stratiform echo structures in the SBC and in other rainbands to determine the vertical structure of heating as a function of horizontal position relative to the storm. We will investigate the implications of the observed heating patterns relative to the storm via numerical modeling. We will use detailed simulations with a high-resolution, nonhydrostatic, full-physics numerical model (see below) to determine the nature of the interactions between the mean vortex and convective and stratiform rainbands at different locations relative to the hurricane.

In summary, the objectives of RAINEX are to document hurricane rainband and inner-core structures to gain insight into how they interact and, ultimately, affect hurricane intensity changes. More specifically, we will:

i. Document rainband and inner-core structures simultaneously by intensive multiple aircraft dual-Doppler radar. These airborne data will determine the evolution and structure of the rainbands relative to their environments and relative to the evolution of the inner-core region of the storm. The radar data will indicate which portions of rainbands are convective and stratiform. The patterns of divergence and vorticity associated with the convective and stratiform precipitation within the rainbands will be identified in the Doppler radar data and used to indicate the spatial configuration of fine-scale PV generation within the rainbands.

ii. Describe the environments of the rainbands from the mid-troposphere down through the hurricane boundary layer by using GPS dropsonde data. These data will provide the thermodynamic framework for the dual-Doppler radar observations of rainband and eyewall structure and dynamics.

iii. Use a high-resolution, non-hydrostatic, and full physics model to investigate the interaction of rainbands and the inner-core region and the impact of this interaction on overall hurricane structure and evolution. The aircraft Doppler radar and dropsonde observations will be used as constraints on what model output can or cannot be considered realistic. The subdivision of rainbands into convective and stratiform region will be examined in relation to the vertical profile of heating and PV generation on the sub-rainband scale. These small scale PV patterns related to latent heating profiles in the convective and stratiform regions will traced in the model through the axisymmetrization process, which is related to storm intensity change (e.g. Montgomery and Kallenbach 1997). The role of convectively induced gravity waves will also be examined in the model context and examined for consistency with the radar and dropsonde data.

The knowledge gained in this study will improve our understanding of hurricane intensity change and will help to improve hurricane prediction models in terms of physical representation of tropical cyclones and, ultimately, storm intensity forecasting.

3. Observational facilities and numerical model to be used in this study

a. Aircraft and airborne radars

The two NOAA P3 aircraft will be requested through Dr. Frank Marks of NOAA/AOML/HRD. These aircraft and their instrumentation are described at http://www.aoml.noaa.gov/hrd. The NOAA P3 aircraft are equipped with both lower-fuselage scanning C-band radars and with tail Doppler radars. We will supplement the NOAA aircraft request by requesting additional dropwindsondes through NSF. The NCAR ELDORA dual-Doppler radar system on board a NRL P3 will be requested from NCAR by the PIs in collaboration with Dr. Wen-Chau Lee. The ELDORA radar is installed on an NRL P3 aircraft. It will provide new views of detailed features of the hurricane rainbands since the ELDORA provides higher time resolution measurements than the NOAA WP-3D aircraft (Wakimoto et al. 1996; Lee et al. 1994). In addition, the use of the NRL P3 with ELDORA will increase the probability of simultaneous Doppler radar coverage in the rainband and eyewall regions (see Section 4b below). A disadvantage of the NRL P3 is that it does not presently have lower fuselage radar scanning capability, so it must fly in coordinated missions with one of the NOAA P3 aircraft. However, the NRL P3 has previously been involved in coordinated missions with the NOAA P3s in BAMEX. We will also request an appropriate number of dropsondes for the NRL P3 through NSF.

b. High-Resolution Mesoscale Model

The proposed study will employ a specialized adaptation of the fifth generation Penn State University/NCAR nonhydrostatic mesoscale model (MM5, Grell et al., 1994) to conduct the numerical simulations. The model will be initialized with the NCEP AVN analysis fields and high-resolution SST data from a combined satellite microwave and AVHRR data, similar to Rogers et al. (2002) and Chen et al. (2004). The version of this model to be used in this study has been developed by Prof. Chen's research group at RSMAS/UM. It features a vortex-following nested-grid that allows long integrations with very high grid resolution in the inner core region of hurricanes. We will use four-level nests with 45, 15, 5, and 1.67 km grid spacing, respectively. We are in the process of developing new data assimilation methodology using both aircraft measurements (e.g., dropsondes and the Doppler winds) and satellite observations (e.g., QuikSCAT and TRMM data) to improve the structure of the initial vortex. The three inner domains move automatically with the storm. The model has been used successfully to simulate

Hurricane Bonnie 1998 (Rogers et al. 2002), Hurricane Georges 1998 (Orndorff et al. 2002), and Hurricane Floyd (Chen et al. 2004, Tenerelli and Chen 2001, 2002).

Figure 2 shows an example of the vortex-following multi-nested grids and the MM5 simulation of Hurricane Floyd. The model initial and lateral boundary conditions (for the outer-most domain) are from the NCEP AVN analysis fields. The model captured (apparently for the first time ever) the development of the concentric eyewalls and a complete eyewall replacement cycle, which was observed in Floyd. A 6-day long animation of MM5 simulation of Floyd precipitation field can be found at http://orca.rsmas.miami.edu/floyd.

4. Experimental Plan

a. Venue for the flight program

It is proposed that the RAINEX flights proposed below be staged from Florida in mature storms of the type that affect the southeastern U.S. As an alternative, they could be staged over the eastern Pacific out of Mexico in coordination with TEXMEX II (see their overview document, Raymond 2004). The latter project is proposed also for 2005, and we are open to a possible joining of our two experiments. However, the emphasis of TEXMEX II is on the early identification and tracking of developing storms; hence, they will operate out of Mexico to take advantage of the climatology of frequent storm formation in the east Pacific with easy aircraft access from the west coast of Mexico. When possible they will also examine storms in their mature stages. This philosophy would decrease the flight opportunities for our mature-stage intensity-change flight program. The Atlantic is the better location for intercepting storms that have already matured and undergoing intensity oscillations as they approach the U.S. Furthermore, the TEXMEX II early-identification and tracking experiment will emphasize sequential P3 flights, while our program for the more mature storms will emphasize concurrent P3 flights, which can assess simultaneously the rainband and eyewall dynamics. It is our premise that understanding the simultaneous behavior of rainband and inner-core structures will lead to insight into the difficult-to-predict intensity changes of storms affecting the U.S. For these reasons, we propose to emphasize simultaneous P3 flights in mature storms in the Atlantic Theatre as our primary experimental focus.

HRD has proposed to coordinate the hurricane research program of 2005 with participants including, TEXMEX II, RAINEX, and the NASA CAMEX 5 project, which will conduct NASA aircraft flights out of Costa Rica. The proposed coordination plan is described in the HRD overview document of Rogers (2004). According to this plan, the P3 aircraft deployments will be controlled by HRD. The NRL P3 is not strictly under HRD control, but they prefer to fly with the NOAA P3 aircraft. The latter will be based in Tampa, but may be directed by HRD to carry out occasional 1-2 week deployments in Mexico. The HRD plan proposes that TEXMEX II operate in the Pacific, out of Mexico, in the earlier part of the hurricane season (July-mid August), when climatology favors hurricanes forming in the Pacific off the coast of Mexico, and that RAINEX will operate out of Florida during mid-August through September, when mature hurricanes typically develop in the Atlantic and threaten the U.S. According to the HRD plan, the overall hurricane research program for 2005 will address the entire hurricane lifecycle and maximize the use of the P3 aircraft Doppler radar facilities available from NOAA and NRL/NCAR in the most appropriate venues.

b. Flight track modules

The flight tracks to be flown in RAINEX are illustrated conceptually in Figure 3. These modules are designed to be simple and adaptable. They will obtain the desired dual-Doppler data with the minimal degree of complexity, and they are readily adaptable in real time to whatever eyewall/rainband configuration presents itself. Module 1 is a dual-Doppler leg flown parallel to a rainband near but outside the inner core of the hurricane. Ideally the rainband chosen for this leg would be the "principal" rainband as described by Willoughby et al. 1984. Module 1 is to be flown on the outside of the rainband, close to and parallel to the rainband, but not within the rainband. This module will be flown by the NRL P3 whenever that aircraft is available. In this way the NRL P3 will not intentionally cross a rainband, as per their flight requirements. To maximize the Doppler coverage, Module 2 will be flown by a NOAA P3, and it consists of a simple "figure 4" pattern across the eyewall region. This will give dual Doppler coverage in 4 quadrants of the eyewall at the same time that the Module 1 aircraft is documenting the rainband kinematics. The orientation of the figure 4 will be adapted in any given storm to give the best overall Doppler coverage of the eyewall. Module 3 is located on the inside edge of the rainband investigated by Module 1.

All the modules assume that GPS-sondes are available, and lower-fuselage Doppler radars are operational on the NOAA WP-3D aircraft. Dropsondes will be obtained as frequently as possible along each flight module. We anticipate a total of ~100 dropsondes per storm. Since the three basic modules are flown primarily near but outside the rainband and eyewall structures, the dropsondes will provide the near environment thermodynamic and shear structures affecting the dynamics of the eyewall and rainbands. We are exploring other aircraft options to intensify the dropsonde coverage in the inner-core and rainband regions.

The NOAA aircraft have lower fuselage radars and extensive hurricane flight experience. They are thus better prepared and equipped to direct multi-aircraft missions in hurricanes. Accordingly, one NOAA aircraft will always be designated as the lead aircraft and the lead scientist on that crew will use the lower fuselage radar to direct all the aircraft in real time. This procedure of modules and their real-time adaptation to circumstances has been used successfully for many years in many field projects.

The three flight modules in Figure 3 can be executed either singularly or in combination. The reality of any aircraft field program is that sometimes all the aircraft are not available. The modules we have designed are robust enough that they can be adapted to whatever combination of aircraft and storm structure occurs. Any individual module in any given storm should provide some useful information on the mesoscale structures and interactions affecting storm intensity changes. If all three aircraft are flying in a storm at the same time, then the modules can be flown simultaneously to give the best possible indication of the ongoing interaction between the eyewall and rainband regions. If all three P3 aircraft are available, Module 3 would occur at the same time as Module 1, to provide quadruple Doppler coverage in the rainband. If only the two NOAA P3 aircraft are flying, then one aircraft will cover the eyewall with Module 2, while the second aircraft will alternate between Modules 1 and 2. If one NOAA P3 flies with the NRL P3, then the former would fly Module 2, while the latter would repeatedly fly Module 1. If only one NOAA P3 is flying, it will alternate between Module 2 and Modules 1 or 3. Any of these flight scenarios will provide useful data, but the plan is to strive to have as many aircraft as possible flying simultaneously.

The simplicity and adaptability of the modules in Figure 3 will allow the data collected by the aircraft to be useful both in individual case studies and statistically. The cases with multiple aircraft coverage will be especially useful for case study analysis. If the modules are applied consistently throughout the program, the data from the modules can also be examined via composite or other statistical analysis methods.

c. Ground activity during the field program

From field program experience (e.g. MAP and IMPROVE II) we know that it is important to lay the groundwork for post-analysis of the type described below by running visualization and analysis software (esp. the ZEBRA software) in the field to develop a set of near real time mission-summary analyses. (The summaries we created in near real time for MAP and IMPROVE II may be viewed at http://www.atmos.washington.edu/%7Ehouze/ WorkiingGroup/iop_summ_rah.html, and http://www.atmos.washington.edu/~houze/improve2_summaries/RadarScientistSummary .html.) These mission summaries guide the data collection in the field as well as the post-analysis. Each new mission can be planned and carried out with the previous missions' preliminary results in mind. We will therefore have an analysis operation set up at the field program headquarters (i.e. HRD in Miami) to develop mission summaries for each mission carried out. These summaries will be on the web after soon after every mission.

The mission summary created on the ground, between aircraft missions will include model output. The University of Miami MM5 will be run in near real time for the storms investigated by aircraft. Thus, some preliminary intercomparison between observed eyewall/rainband evolution and model storm development can be made after flights have been conducted. The model runs will be done as soon as the NCEP 3-5 day forecast is available to supply boundary conditions to the MM5. The results of comparing the aircraft data to these near real-time model runs will be used to guide the next mission. This procedure of examining high resolution model simulations of observed cases in near real time has guided the missions summaries in past projects such as MAP and IMPROVE II. We will follow analogous prodedures in RAINEX.

5. Modeling and analysis plan

a. Pre-experiment modeling and analysis plans

Previous simulations by Professor Chen's group of Hurricanes Floyd (1999), Bonnie (1998), Georges (1998), and Lili (2002) have successfully shown a distinct set of rainbands and inner-core structures. Floyd was a strong category-4 hurricane with fully developed concentric eyewalls and eyewall replacement cycle (Chen et al. 2004, Tenerelli and Chen 2002), whereas Bonnie a category 2 storm with asymmetric rain distribution under a very strong wind shear environment (Rogers et al. 2002). Georges exhhibited a rapid weakening, from a category 4 to category-2 hurricane within 12-18 hours with a strong dry-air intrusion into inner core between rainbands, before approaching the Caribbean Islands (Orndorff et al. 2002).

During the 2003 Hurricane season two major hurricanes, Fabian and Isabel, developed in the Atlantic basin. The peak intensity reached 125 knot (Category 4) and 145 knot (Category 5) for Fabian and Isabel, respectively. Both hurricanes went through a rapid intensification before reaching their maximum intensity. Isabel remained as a Category 4-5 hurricane for more than four days from September 10-15 and then went through relatively fast weakening to a Category 2 storm on September 16. Both storms displayed complex inner core and rainband structures. Isabel went through several eyewall replacement cycles. Fabian and Isabel were observed extensively by two NOAA PW-3D aircraft during the CBLAST-Hurricane field program with three dual-aircraft missions for each of the storms. A large set of Doppler radar data, dropsondes, boundary layer and sea state measurements was collected (although not according to flight plans optimized for our study). Thus, Fabian and Isabel are excellent cases for further preliminary modeling and analysis culminating in the RAINEX program in 2005.

We will conduct simulations of Fabian and Isabel and make a preliminary analysis of the 2004 flights to lay the groundwork for RAINEX in 2005. We will conduct "virtual" flights on the model output of these storms by examining the results that would have been by applying the flight modules in Figure 3 to the model output.

b. Post experiment modeling and analysis plans

The primary objective of this research is to understand hurricane intensity changes in relation to inner-core interactions with rainbands using combined analyses of model output and aircraft observations. We will use the Zebra analysis software to analyze simultaneously the airborne observations and model output for Hurricanes Fabian and Isabel (2003) and the 2004 storms flown in conjunction with CBLAST. We will focus on the rainband locations and patterns in relation to the inner core structure in each of the storms. We will determine the locations of stratiform and convective regions in the rainbands and eyewall in the radar observations and determine the degree to which the model also represents the convective and stratiform substructure accurately. From the model winds and the radar dual-Doppler winds, we will determine whether the model is portraying accurately the patterns of vorticity within the rainbands and eyewall. We will also use the dropsonde data and flight level data in the analysis of the vorticity structure of the rainbands and eyewall. In addition we will explore and develop new methods to use the airborne data to initialize the vortex in MM5 high-resolution inner nests with realistic fine structures. Numerical experiments will be conducted to determine the factors that lead to agreement between the observed and model rainbands and eyewall regions. Once we obtain model simulations that agree reasonably with the aircraft radar wind and vorticity patterns, the model output will be used to determine the potential vorticity evolution within the rainbands and eyewall. From the model we will further determine how this potential vorticity evolution in the eyewall and rainbands relates to storm intensity changes and eyewall replacement cycles. We will thus diagnose the fundamental dynamics, development and interactions of rainbands, eyewalls and their relation to intensity changes. These analyses will help us begin to understand some aspects of rainband and inner core interaction that affect forecasting of intensity changes of hurricanes affecting the U.S.

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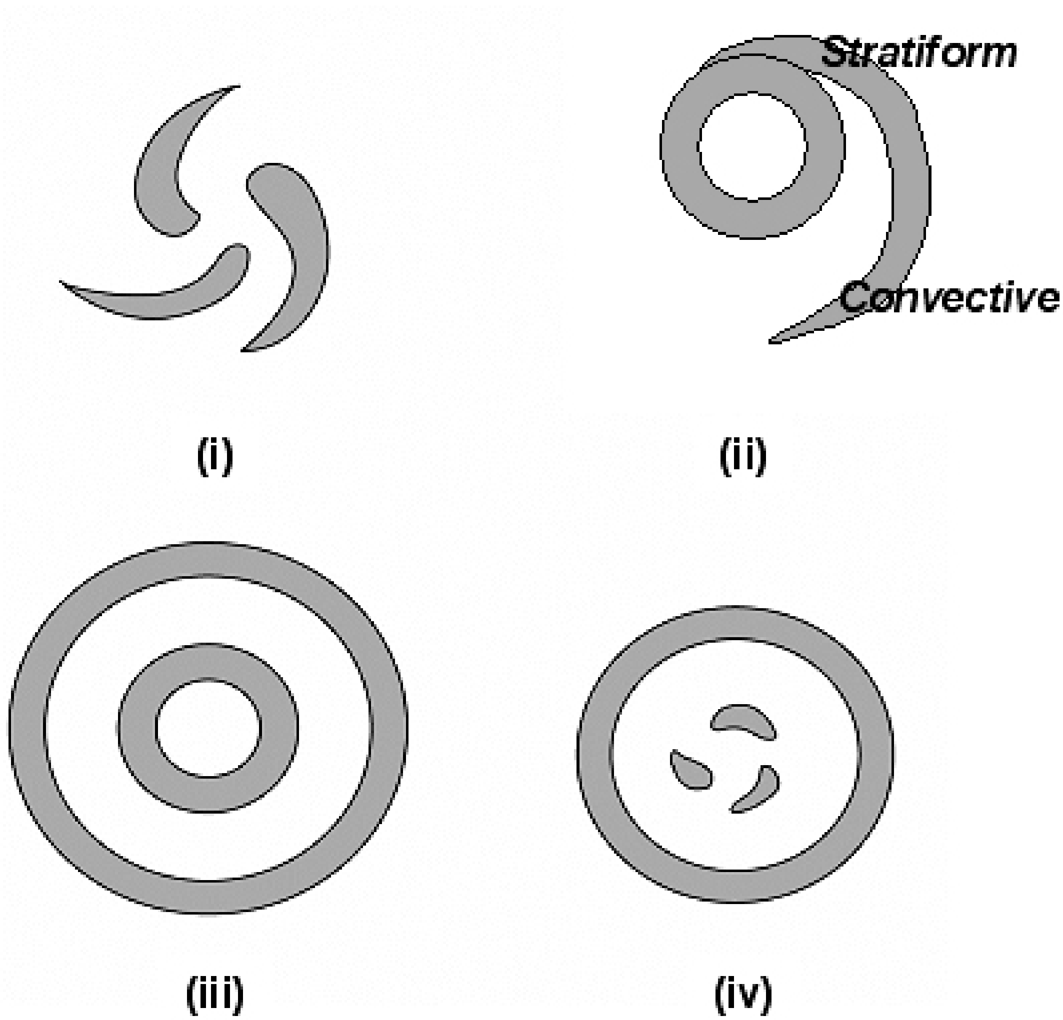

Figure 1. Schematic of four stages of hurricane rainbands and eyewall.

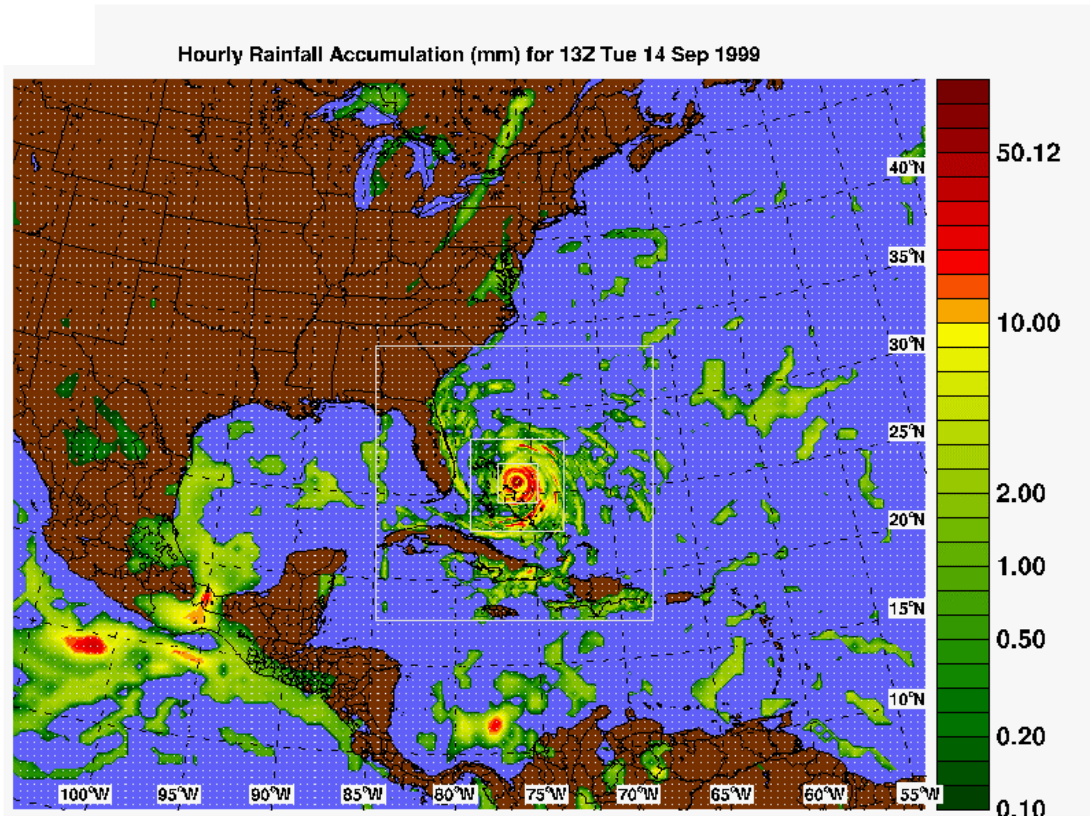

Figure 2. MM5 simulation of Hurricane Floyd (1999) surface rainfall with vortex-following nested grids of 45, 15, 5, and 1.67 km grid spacings, respectively.

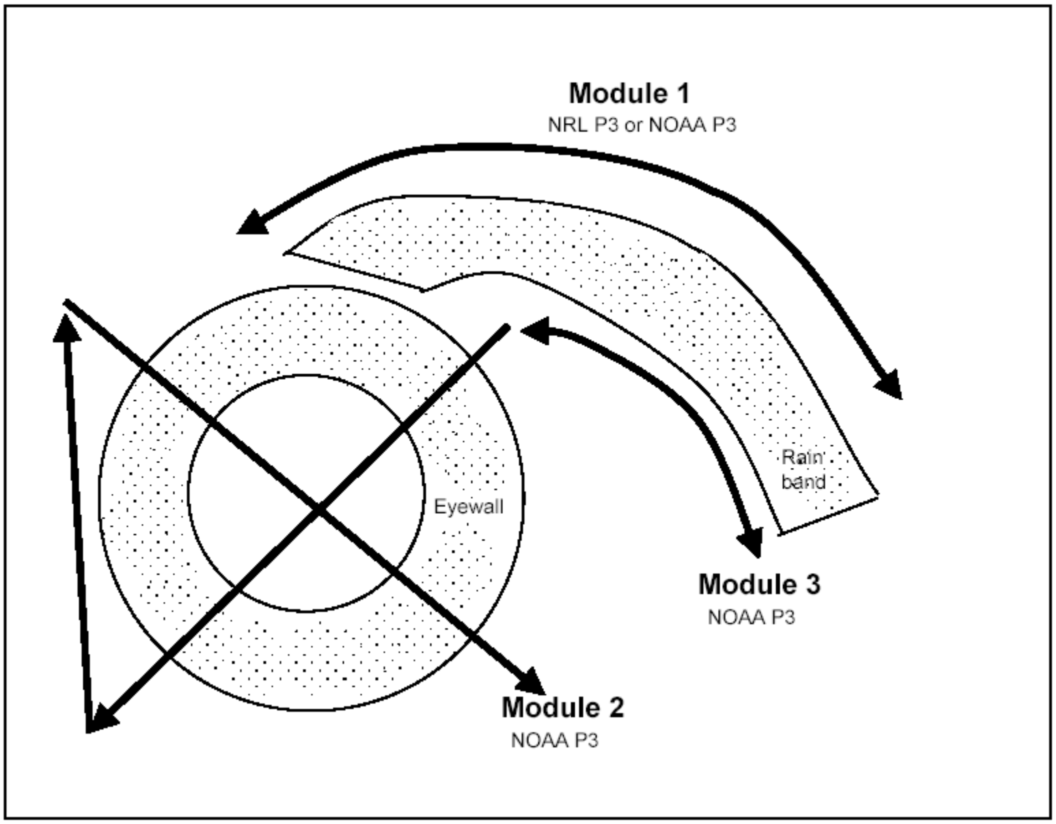

Figure 3. RAINEX flight modules.