Collaborative Research: Impact of Externally and Internally Modulated Convection on Tropical Cyclone Evolution

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Directorate: Geosciences
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Project Summary

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The objective of the proposed research is to develop an improved understanding of the convective response of a tropical cyclone's core to external forcing and internal dynamics. The impact of this convective response upon the ensuing evolution of an externally forced tropical cyclone is then examined. In the particular case of a vertically-sheared tropical cyclone, convection has been argued to have both positive and negative influences on vortex structure and intensity. The proposed research will attempt to clearly define the role of convection by examining the impact of vertical shear on a moist-convective vortex within a simplified wave-mean dynamical framework.

The proposed research employs a combined observational and numerical modeling approach. The observations are derived from airborne dual-Doppler radar measurements within a rapidly intensifying, yet vertically-sheared, hurricane. A unique three-dimensional documentation of the hurricane structure and evolution, including the eye-eyewall interface and upper-tropospheric vortex circulation, will be used to examine the nature, timing, and location of convection within the vortex core. These observations, supplemented with additional collected data, will be used to represent convection in a series of idealized numerical simulations. The idealized simulations are designed first to elucidate the role of convection in tropical cyclone resiliency, and then to determine how and when convection begins to impact the tropical cyclone negatively.

Intellectual Merit: The proposed research will provide new insights into i) the observed three-dimensional mixing between eye and eyewall within a rapidly intensifying hurricane, ii) the observed convective asymmetry within a vertically-sheared hurricane, iii) the role of convection in vertically-sheared hurricane resiliency, and iv) the role of deep cumulus convection in the weakening of a vertically-sheared hurricane. The latter two points are approached from a wave-mean perspective which encompasses both the vortex vertical tilt and convective asymmetry evolution.

Broader Impacts: The proposed activities will have several broader impacts. Regarding hurricanes: Presently, there exists a single observational study of the three-dimensional hurricane vorticity dynamics. The proposed case study is an important step towards increasing the statistical database of three-dimensional observations, which is crucial if such data are to be meaningfully assimilated into mesoscale numerical forecast models. Additionally, the proposed mapping of effective stratification based on observed data within the hurricane core may be used by future investigators for idealized numerical modeling. More generally: The convection-vortex interaction is a general atmospheric problem (e.g., mid-latitude MCVs) and has parallels with the convectively-coupled equatorial wave problem. The proposed study draws upon this broader knowledge base, and in return will contribute beyond the scope of hurricanes. Two graduate students and an undergraduate will be trained in the techniques of radar data editing and analysis, atmospheric dynamics, and numerical modeling. These students will also be encouraged to interact with scientists at NOAA's Hurricane Research Division through their ongoing cooperation with the universities.

PROJECT DESCRIPTION

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1. Objectives and Significance:

Our objective is to examine the mechanisms controlling the timing, location, and intensity of asymmetrically-distributed convection in the tropical cyclone (TC) core, and the feedback of the convective asymmetry on the vortex using unique observational datasets and idealized numerical simulations. The approach taken here is predicated on the testable hypothesis that the predominant convective asymmetry in the TC core (or eyewall) is a consequence of quasi-persistent storm-motion and vertical-shear forcing, modulated by distinct low-azimuthal wavenumber internal phenomena. The extent to which a mesoscale representation of this convective asymmetry is a reasonable starting point for addressing the vertically-sheared TC intensity problem is a primary question underlying the proposed research. Specific objectives of this study are then:

1. Document the evolution of the low-azimuthal wavenumber and convective structure of an observed intense TC throughout much of its depth, highlighting quasi-persistent storm-motion and vertical-shear induced asymmetries, and their internal modulation.
2. Extend a recent wave-mean theory for TC resiliency in vertical shear flow to include moist convective processes.
3. Clarify the impact of evolving asymmetric vortical structures (e.g., vortex Rossby waves and mesovortices) on the spatial distribution of convection in the TC core.
4. Utilize the findings from the above objectives to identify which processes are *essential* for modeling the intensity response of a TC to external forcing.

The expected significance of this proposed research is as follows:

1. Unprecedented documentation of the basic three-dimensional (3D) structure *and* evolution of an observed rapidly intensifying TC for better representation in numerical model initializations
2. Extension of airborne Doppler radar's application to include the study of the dynamical evolution of the upper tropospheric TC circulation and the eye-eyewall interaction
3. A theoretical framework for examining the feedback of asymmetric convection on vertically-sheared convective vortices which incorporates both positive and negative dynamic and thermodynamic impacts on intensity
4. A realistic inclusion of eye-eyewall interaction and the modulation of convection by evolving asymmetric structures into the current conceptual model of TC structure and evolution

2. Background and Motivation

The TC is a potentially destructive warm-core atmospheric vortex common to all tropical ocean basins. Recent advances in our understanding of the basic physics governing the TC have yielded significant improvement in the forecasting of storm track. The associated forecasts of storm intensity, however, have not shown the same improvement due to an incomplete understanding of the complex external and internal processes which influence intensity (Elsberry et al. 1992; DeMaria and Kaplan 1999). In particular, it is well known that latent heat release in the TC eyewall is crucial for maintenance of the warm core, but the nature, timing, location, and intensity of the heating and its interaction with (and feedback on) the primary vortex are not well understood.

Early studies of the TC approached the problem of discerning the basic governing mechanisms from an axisymmetric viewpoint, neglecting azimuthal variations about the storm center. Aircraft observations have largely supported a "zeroth-order" circularly symmetric model of the TC (e.g., LaSeur and Hawkins 1963; Hawkins and Imbembo 1976; Jorgensen 1984a,b; Willoughby 1990). Axisymmetric numerical models have reproduced many observed structural characteristics of the axisymmetric component of the TC and mimicked observed vortex evolution to a first approximation (e.g., Ooyama 1969; Rotunno and Emanuel 1987; Willoughby 1990).

A few early studies noted asymmetric processes may play a non-negligible role in TC evolution (Malkus 1958; Riehl and Malkus 1961), but considerable interest in the asymmetric dynamics has only recently developed. This interest was spurred by the recognition that the TC rarely evolves in a quiescent environment, and is therefore subject to forcing which, at times, may bring about significant departures from axisymmetry in both the vortex flow and convective fields. This forcing includes interactions of the TC with synoptic-scale troughs (e.g., Molinari and Vollaro 1989; Molinari et al. 1995), uniform flow (e.g., Shapiro 1983), and vertically sheared flow (e.g., Frank and Ritchie 1999, 2001). The generation of pronounced asymmetry, however, is not limited to external interactions, but can also arise internally through vortex instabilities (e.g., Schubert et al. 1999; Nolan and Montgomery 2002).

2.1. TC asymmetry and intensity change

The interaction of the axisymmetric TC circulation with asymmetrically distributed convection has received particular attention because of its potential role in structure and intensity change. Recent idealized studies of the TC have parameterized the asymmetric convection in terms of its ultimate impact on the asymmetric (potential) vorticity field (Montgomery and Kallenbach 1997; Montgomery and Enagonio 1998; Möller and Montgomery 1999; Möller and Montgomery 2000; Shapiro 2000), and alternatively in terms of its initial impact on the asymmetric thermal field (Nolan and Montgomery 2002; Nolan and Grasso 2003). In nature the thermal anomaly generated by convective heating must first go through an adjustment process, the end result of which is a balanced vortical flow. In a rapidly rotating flow such as the TC the transient adjustment is quite efficient, projecting relatively little energy onto fast gravity wave motions (Schubert et al. 1980). Thus, in the former approach to the convective asymmetry problem the adjustment process is bypassed, and the assumed balanced vortical end state is used to initialize the model. Nolan and Grasso (2003) have shown that while the adjustment may be rapid, the axisymmetric TC circulation nevertheless can be modified in a non-negligible way during the transformation of an initial unbalanced thermal asymmetry into a balanced vorticity asymmetry. Simulations initialized with balanced vorticity asymmetries generally yield intensification of the axisymmetric vortex through a “wave-mean” interaction involving vortex Rossby waves (VRWs – the vortex analog of the familiar Rossby wave, but with the radial gradient of axisymmetric vorticity serving as the restoring mechanism). Nolan and Grasso (2003) found that in most cases a vortex initialized with a thermal asymmetry (not including an axisymmetric component) will ultimately weaken.

Shapiro (2000) utilized a three-layer model with a convergence-based convective parameterization to examine the impact of cumulus convection and boundary layer processes on the evolution of initially balanced vorticity asymmetries within a mature TC. The early interaction of the axisymmetric vortex with the vorticity asymmetry differed from the predictions of dry experiments. The pattern of axisymmetric wind acceleration and deceleration associated with the VRW wave-mean interaction was largely independent of the initial radial location of the asymmetry. The ring-like radial profile of potential vorticity and the stretching of asymmetric vorticity by the axisymmetric secondary circulation, both consequences of moist processes, were found to be responsible for the differences from dry predictions (e.g., Möller and Montgomery 1999). The long-term evolution of vortex intensity in the moist simulations also departed from the long-term net intensification found in dry studies. In the moist case, the VRW wave-mean interaction caused a reduction of the peak axisymmetric vorticity, which was then followed by a reduction of the axisymmetric upward vertical velocity at the top of the boundary layer within the eyewall (i.e., Ekman-like pumping). The subsequent reduction in convective mass flux then produced a net weakening of the axisymmetric vortex.

Clearly, the choice of convective asymmetry parameterization has great impact on the ensuing evolution of the axisymmetric vortex. How best to parameterize the TC core convection for the purpose of idealized numerical modeling remains an open question. While one might argue that the idealized representation of cumulus convection, or ensemble of convective events, is closest to the pure unbalanced thermal asymmetry, this view seems to neglect the possibility of significant vortex stretching within the rising thermals. Eastin et al. (2005a,b) recently demonstrated that numerous positively buoyant convective updrafts are superimposed on the mesoscale current of rising motion that composes the eyewall. The buoyant updrafts occupy less than 5% of the total eyewall area, but accomplish 40% of the total upward mass transport. These accelerating updrafts should also accomplish enhanced vortex stretching of the large reservoir of vertical vorticity in the eyewall, producing asymmetric vorticity. **An emphasis of the present proposal is on documenting the thermodynamic and kinematic structures of observed eyewall convection**.

2.2. Sources of TC convective asymmetry

Idealized studies of the dynamical interaction of the axisymmetric TC vortex with convective asymmetries have not included the external forcing mechanisms often responsible for a considerable portion of the convective asymmetry (see section 2.3 below for a recent exception). The addition of external mechanical forcing adds an additional layer of complexity to the problem, but is essential for a complete treatment of intensity change. We focus on the two most often-cited sources of externally forced TC convective asymmetry, storm motion and vertical shear.

Shapiro (1983) utilized a simple slab boundary layer model to demonstrate the impact of asymmetric frictional drag on TC boundary layer convergence. Asymmetric drag arises naturally as a consequence of storm translation. Shapiro found that the location of maximum convergence occurs in the front quadrant relative to the direction of storm motion, and shifts clockwise into the front-right quadrant as the translation speed increases. Thus, quasi-persistent (i.e., on the timescale of several eyewall orbital periods) asymmetric convection would be preferred in the front to front-right quadrant via this mechanism.

Another source of asymmetric convection is the interaction of the TC with vertically sheared environmental flow. In dry numerical models the vertical shearing of a TC-like vortex produces enhanced upward motion in the vortex core initially in the downshear direction, and then in the down*tilt*-right direction as the vertical tilt of the vortex increases (Jones 1995). Moist numerical simulations of the TC in vertical shear generally produce a quasi-persistent convective asymmetry in the downshear to downshear-left quadrant of the storm (Wang and Holland 1996; Bender 1997; Frank and Ritchie 1999, 2001). A study of hurricane lightning data by Corbosiero and Molinari (2003) supports a strong correlation between the quadrant of maximum deep convection and the direction of environmental vertical shear. Individual hurricane case studies (e.g., Marks et al. 1992; Reasor et al. 2000, hereafter R00; Black et al. 2002) also indicate a strong relationship between the spatial orientation of eyewall convective asymmetry and the direction of vertical shear.

A portion of the total convective asymmetry can also result from internal forcing mechanisms. The hurricane eyewall is sometimes observed to exhibit an elliptical or polygonal structure with convection organized asymmetrically (e.g., Lewis and Hawkins 1982; Muramatsu 1986; Kuo et al. 1999; R00). Schubert et al. (1999) examined the barotropic instability of hurricane-like profiles as a possible source for this deviation from axisymmetry. The distribution of potential vorticity within a mature hurricane often resembles a "hollow tower" due to potential vorticity production within the convective eyewall. The change in sign of the radial potential vorticity gradient permits barotropically unstable modes to grow within the vortex core, promoting mixing between eye and eyewall. If the unstable modes are able to grow to finite amplitude, or are strengthened by vortex stretching, mesovortices may also arise within the vortex core as part of the mixing process. These mesovortices give the eyewall its polygonal structure. Kossin and Eastin (2001) documented several observed hurricane cases where such instability and mixing likely occurred.

Through modulation of eyewall convective asymmetry, the internal mechanisms discussed above can impact TC intensity. The average mesoscale thermodynamic structure of the eyewall is not inherently conducive to traditional buoyant convection due to the outward-sloping equivalent potential temperature (θ_e) surfaces (Hawkins and Imbembo 1976; Jorgensen 1984b; Eastin et al. 2002b). Thus, the eyewall region is locally stable to pure vertical convection, but conditionally unstable to slantwise convection. However, given that the low-level eye typically contains high-θ_e air relative to the eyewall (e.g., Willoughby 1998), local buoyant instabilities could be generated through outward advection of eye air into the eyewall via the barotropic instability and mixing mechanism. Comparing θ_e observed at aircraft flight level to multiple vertical θ_e profiles observed at various radii below flight level, Eastin et al. (2005b) demonstrated for two intensifying hurricanes that the only potential source of air within several buoyant eyewall updrafts was the low-level eye. Recent moist numerical simulations of Braun (2002) and Persing and Montgomery (2003) support this link between internally generated vortex asymmetries and eyewall convective asymmetry. **How internally-generated vortex asymmetries modulate the quasi-persistent convective asymmetry due to storm motion and vertical shearing is a significant focus of the proposed work**.

2.3. The TC in background flow: Idealized modeling of convective asymmetry

The primary emphasis of the proposed numerical study is on understanding how convection and convective asymmetry impact the evolution of the TC in vertical shear flow. In their moist numerical simulations of TCs in vertical shear flow, Frank and Ritchie (1999; 2001) suggested that "the processes that act to make the eyewall axisymmetric" are countered by processes associated with the development of convective asymmetry. They speculated that at some point the positive axisymmetrizing mechanisms are unable to hold off the erosion of the upper potential vorticity structure of the TC and subsequent flux of high θ_e out of the vortex core. As a consequence, the TC weakens from top-down. The mechanisms contributing to *resiliency* of the TC are clarified below.

Reasor et al. (2004; hereafter RMG04) proposed a new paradigm for the TC in vertical shear flow which explains the resiliency of the vortex through an intrinsically dry dynamical mechanism. They hypothesized that the zeroth-order impact of moist convection on TC resiliency is to increase the efficiency of this mechanism. When an initially barotropic vortex of TC-like radial structure is given a small, but finite-amplitude vertical tilt, the vortex realigns. The vertical alignment occurs through the projection of the vortex tilt asymmetry onto VRWs. For typical tropical values of static stability, Coriolis parameter, and vortex depth, the vortex tilt projects strongly onto a VRW with modal characteristics (i.e., a radial structure that remains intact, and an exponential decay of amplitude with time). The mode is confined to the vortex core, and interacts with the surrounding flow. In the region of the flow where the precession frequency of the VRW core mode, as we will refer to it, equals the angular rotation rate of the vortex, a critical layer is established. As discussed by Schecter et al. (2002) and Schecter and Montgomery (2003), mixing in the critical layer must be accompanied by damping of the VRW core mode, and thus alignment of the vortex. The rate of damping is proportional to the radial gradient of axisymmetric vorticity within the critical layer. This so-called “resonant damping” mechanism is made more efficient through the reduction of static stability because the critical layer tends to shift radially inward into the region where the radial vorticity gradient is strongest. In saturated flow static stability is reduced in the presence of vertical motion (Durran and Klemp 1982). The TC eyewall, where ascending motion is prevalent, is then a location of reduced static stability. The resonant damping of the VRW core mode (i.e., the vertical tilt) is enhanced within moist convective vortices, but convection is not believed fundamentally responsible for the vertical alignment.

In the above conceptual framework vertical shear is a VRW generator, exciting both the horizontally sheared VRWs described by Montgomery and Kallenbach (1997) and the resonantly damped VRW core mode. RMG04 showed that when a TC-like vortex supporting a VRW core mode is forced by vertical shear flow, it behaves as a forced, damped harmonic oscillator. When the resonant damping rate and precession frequency of the VRW core mode are greater than the differential advection rate of the vortex by the shear flow, the vortex achieves a steady state vertical tilt to the left of the vertical shear vector. When the VRW core mode precesses too slowly, differential advection by vertical shear tends to tear the vortex apart. RMG04 further showed that hurricane-strength vortices supporting a VRW core mode can remain vertically aligned without the aid of moist processes in vertical shears exceeding 10 ms^{-1} over the vortex depth. These dry results support the hypothesis that convection is not fundamentally responsible for the resiliency of TCs in vertical shear flow. Convection is, however, clearly required to maintain the axisymmetric vortex circulation against frictional drag in the boundary layer.

How the above resiliency theory for the TC would be modified by the “diabatically-driven” axisymmetric secondary circulation and the presence of asymmetric moist convection has not yet been examined. A preliminary attempt at including the impact of asymmetric latent heating (associated with the weak mesoscale ascent driven by the vortex-shear interaction) upon the vortex evolution was made by Patra (2004). Patra assumed that diabatic heating is directly proportional to vertical velocity. Thus, where their dry 3D primitive equation model predicts upward (downward) motion, diabatic heating (cooling) occurs. This parameterization of heating modifies the thermodynamic equation such that the dry static stability is replaced by a reduced moist static stability. The reduced static stability is only applied within the vortex core, and takes on its dry value outside the core. As expected from arguments above, the reduced static stability simply yields a more resilient vortex with maximum ascent downtilt-right. In the singular limit of neutral stability (to purely vertical motions) Patra observed a very different vortex evolution. The maximum ascent concentrates in the downshear-left quadrant, in apparent agreement with moist numerical simulations. The development of horizontal potential vorticity filaments was argued to aid the resiliency of the vortex in this case, but the precise dynamical mechanisms remain unclear. **In the work proposed here the heating will be included within the framework of the VRW dynamics, providing the possibility for a unification of the vortex resiliency and convective asymmetry (section 2.1) ideas**.

2.4. Three-dimensional observations of TC asymmetry

Numerous past studies have utilized airborne Doppler radar data to diagnose asymmetric low-wavenumber features within the TC wind field. The first study by Marks and Houze (1984) examined Hurricane Debby (1982). Small scale eddies were found embedded within the primary vortex circulation. A coherent mesovortex was also documented within the developing eyewall. They speculated that advection of the mesovortex toward the storm center may have influenced the evolution of the hurricane. The dataset, however, lacked the temporal continuity needed to verify such mesovortex advection. Subsequent studies using airborne Doppler radar provided more complete mappings of the TC wind field (Marks and Houze 1987; Marks et al. 1992; Dodge et al. 1999), but the required use of pseudo dual-Doppler techniques limited the construction of 3D wind fields to composites spanning several hours. Coherent asymmetries were noted, but information on the time evolution of the asymmetries was unavailable.

More recently, R00 documented the low-wavenumber structure and evolution of Hurricane Olivia (1994) using seven unique composite wind fields spanning a 3.5 h period. Each 3D composite was constructed from measurements made within a 10-15 minute period, and thus provided rough “snapshots” of the wind field from which to deduce evolution. Vertical wind shear increased dramatically during the observation period, leading to a persistent wavenumber-one convective pattern oriented along the maximum vertical shear vector. A wavenumber two pattern dominated the asymmetric relative vorticity field below 3 km height. The evolution of its amplitude and vertical structure were documented. Lower-fuselage reflectivity during one pass through the storm indicated a rotating elliptical eyewall with major axis coincident with the positive vorticity of the wavenumber two asymmetry. R00 used idealized barotropic numerical simulations to suggest that the observed changes in Olivia’s axisymmetric and asymmetric vortex structure were consistent with barotropic instability of the vortex. Outside the eyewall, small-scale (5-10 km across) spiral bands of vorticity were observed coincident with bands of elevated reflectivity. It was suggested that these bands might be manifestations of sheared VRWs, but without adequate time continuity propagation characteristics could not be directly ascertained. As part of the present proposed research, the various vortex features identified by R00 will be re-examined in the context of a new case study which is comparable to the Olivia case, but with distinct advantages and unique aspects to be described in section 4.1.

3. Relationship to longer-term goals of the PIs

The first PI (Reasor, Florida State University) seeks to understand the feedback of moist convection on the structure, intensity, and longevity of vertically-sheared atmospheric vortices. The PI has led the development of a new paradigm for the TC in vertical shear flow which explains TC resiliency in terms of an intrinsically dry dynamical mechanism. Neglected in the PI’s prior work is the response of the vortex to asymmetric convection forced by vertical shearing. This asymmetric convective response, the subject of the present proposed research, is likely key to accurate prediction of vortex evolution in vertical shear. The focus here is on the TC, but in keeping with the longer-term goals of the PI, the proposed research will lay the foundation for future studies of atmospheric vortices on a wide range of scales. An additional long-term goal of the PI is to determine how airborne and ground-based Doppler radar data may be best utilized in mesoscale model assimilation schemes. The proposed study of the basic mechanisms involved in the TC-in-shear problem will guide future attempts to selectively extract essential (e.g., dynamically relevant) flow and reflectivity features from the Doppler radar data.

Previous and current research by the second PI (Eastin, Central College) has focused primarily on documenting kinematic and thermodynamic characteristics of TC inner-core convective structure and evolution via extensive observational analysis. These studies have diagnosed relationships between the presence of deep buoyant convection, dramatic transitions in radial structure, mesovortices embedded along the eye-eyewall interface, and TC evolution. Such observations are crucial for the development of realistic conceptual models concerning the origin, nature, and organization of TC convection as well as its positive and negative impacts upon vortex evolution. Thus, the proposed research both complements and extends ongoing work by providing a fully “four-dimensional” context in which to explore such relationships.

4. Proposed Research

The broad objectives of the proposed research are 1) to determine the primary mechanisms for the generation and modulation of convective asymmetry in an observed translating, vertically-sheared TC and 2) to develop a model for the feedback of convective asymmetry upon the structure and intensity of a translating, vertically-sheared TC. The first objective is addressed using a unique dual-Doppler, aircraft in-situ, and GPS dropwindsonde dataset documenting the rapid intensification of Hurricane Guillermo (1997) over a two-day period (sections 4.1 and 4.2). While it is well known that translation and vertical shearing of a TC often yield a quasi-persistent eyewall convective asymmetry, the mechanisms by which the external forcing and convective asymmetry conspire to produce structure and intensity change are not well understood. Thus, the second objective is addressed through observationally-motivated idealized numerical simulations in which externally-forced convective asymmetry is parameterized and then examined for its impact on TC structure and resiliency (section 4.3). Details concerning the data analysis methods, numerical simulations, and specific research plan are discussed in section 4.4.

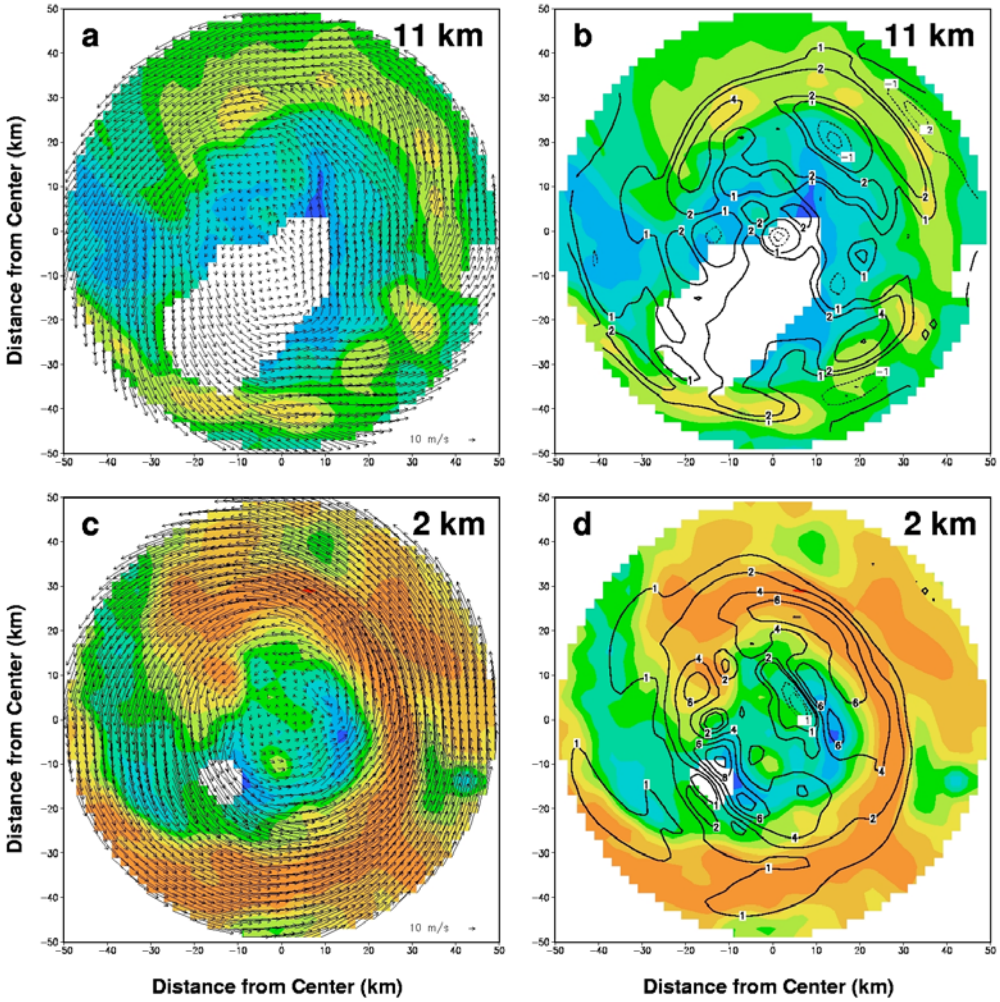

Figure 1. Dual-Doppler derived storm-relative wind vectors, vertical vorticity, and radar reflectivity at 2 and 11 km altitude for Hurricane Guillermo between 2105 and 2126 UTC on 2 August 1997. Reflectivity is shaded at the -7, 0, 5, 10, 15, 20, 25, 30, and 35 dBZ levels. Vertical vorticity is contoured for -2, -1, 1, 2, 4, 6, and 8 x 10^{-3} s^{-1}. Winds within unshaded regions were "filled-in" by the variational analysis method. Note the exceptional coverage of Doppler-derived winds throughout much of the eye at both levels.

4.1. Dual-Doppler radar analyses

Documentation of the structure and evolution of the 3D TC wind field is an important objective of recent observational field campaigns (e.g., the Hurricane Research Division's Annual Field Program; NASA's CAMEX experiments). To date the number of published studies of the observed *evolution* of the 3D TC wind field is relatively small, as discussed in section 2.4. The study of Hurricane Olivia (1994) by R00 was the first, and at present only, to employ airborne dual-Doppler radar to examine the inner-core vorticity dynamics of a mature TC. In the proposed study of Hurricane Guillermo (1997) we will again examine the inner-core evolution of a mature vertically-sheared TC using dual-Doppler measurements. In distinction to R00, a greater emphasis will be placed on the convective structure of the eyewall and on a more focused examination of the storm's interaction with its environment. While a re-examination of Hurricane Olivia (1994) is suggested as part of this proposed research, the Guillermo case offers exciting new research opportunities, as discussed below.

The observational analysis undertaken here broadly follows R00, but capitalizes on a dataset with considerably fewer limitations. Two National Oceanic and Atmospheric Administration (NOAA) WP-3D (P3) aircraft, each equipped with 3-cm tail Doppler radar and 5-cm lower-fuselage radar, made repeated simultaneous penetrations through eastern Pacific Hurricane Guillermo over two 6 h periods on 2 and 3 August 1997. Raw data from the tail and lower-fuselage radars of the P3 aircraft were made available by Dr. Frank Marks of NOAA's Hurricane Research Division (HRD). The analyzed dataset (see section 4.1.1 for analysis details) will consist of 20 unique 3D dual-Doppler wind composites of the vortex core over the two day observation period.

In terms of an overall snapshot of the TC wind, thermodynamic, and microphysical fields, the Guillermo dataset is not as thorough as that obtained in the recent CAMEX investigation of Hurricane Humberto (2001) (Gamache et al. 2004). Humberto, however, was a relatively weak and highly asymmetric storm. The asymmetry in Humberto's precipitation pattern in particular limited the ability of Doppler radar to sample the full 3D structure of the wind field. Guillermo, on the other hand, was a strong, largely axisymmetric storm, with an eye filled with clouds and light precipitation on both days. This fortuitous distribution of scatterers will permit unprecedented documentation of the wind field across much of the eye and eyewall throughout the troposphere (Fig. 1). Also distinguishing the Guillermo Doppler dataset is the relatively short 30-40 min temporal gap between each day's 10 composited wind fields compared to the 50-60 min orbital period of parcels within the eyewall. This temporal continuity permits greater resolution of evolving asymmetric structures than was available in R00's Olivia case. Furthermore, Guillermo rapidly intensified on the first day at a mean rate of -2.4 mb/hr from an initial minimum sea level pressure of 959 mb. To date the 3D wind field evolution of a rapidly intensifying hurricane has not been observationally documented; <u>this study will provide the first case</u>. Finally, the rapid intensification occurred in spite of an estimated local vertical shear (see section 4.4.1) exceeding 10 m/s over Guillermo's depth. Observations of Guillermo's wind field on the second day will provide an additional case of a strong, steady-state vertically-sheared hurricane near maximum intensity.

We propose to document Guillermo's evolving vertical tilt, axisymmetric structure, and asymmetric structure with the goal of understanding how the vortex was able to rapidly intensify within an environment of non-negligible vertical shear. Upon constructing the 3D wind fields from the raw dual-Doppler data following the methodology outlined in section 4.4.1, the flow will first be decomposed into its azimuthal wavenumber components. The purpose of this decomposition is to quantify and characterize the vortex asymmetry. To quantify the vertical tilt, various center finding methods like the Simplex algorithm (Marks et al. 1992; R00) and vorticity centroid (Jones 2004) will be employed. RMG04 proposed that when a TC is nearly vertically aligned, it is conceptually useful to view the small tilt of the TC as an evolving small-amplitude asymmetry on the axisymmetric component of the vortex. Whether such a treatment of the vortex is justifiable in this case will be determined.

The next step in the analysis is to characterize the convective asymmetry in terms of its orientation relative to the directions of storm motion and Doppler-estimated local vertical shear. The objective is to determine the source of the quasi-persistent component of the convective asymmetry, which may in turn be modulated by internal phenomena discussed below. R00 showed that the downshear vertical motion asymmetry in Olivia intensified as the local vertical shear increased and storm motion remained approximately constant. Preliminary estimates of the local vertical shear of Guillermo superimposed on radar reflectivity on both days suggest a similar relationship between shear and convective asymmetry (Eastin et al. 2004).

Because the standard dual-Doppler analyses of the vortex core have horizontal resolution of approximately 2 km and a typical compositing time of 10-15 min, details of individual convective cells are not available. However, by limiting the Doppler domain to individual quadrants of the eyewall, we can decrease the compositing time of the analyses to yield reliable snapshots of the mesoscale region of convective asymmetry. **Through such analyses we will document how vorticity evolves within the regions of quasi-persistent convective asymmetry**. Most idealized studies of convective asymmetry within TC-like vortices assume that the end result of a series of deep convective events is a balanced mesoscale vorticity asymmetry, which is subsequently axisymmetrized. This Guillermo dataset offers the possibility of documenting observationally for the first time what this vorticity asymmetry looks like spatially and how it evolves. Methods for obtaining thermodynamic aspects of the convective asymmetry are addressed in section 4.2.

Convection within the TC core may also be modulated through internal vortex dynamics. R00 provided evidence for a rotating azimuthal wavenumber two vorticity asymmetry within the eyewall of Olivia, and suggested barotropic instability of the vortex as a likely source. In the context of a numerically-simulated hurricane, Braun (2002) showed that the perturbation flow associated with especially robust low-wavenumber vortical structures can modulate convection within the eyewall. Such low-wavenumber structures are thought to be part of a more general asymmetric mixing between the eye and eyewall, previously cited as a source of deep eyewall convection (Malkus 1958; Marks et al. 1992; Willoughby 1998; R00; Kossin and Eastin 2001; Eastin et al. 2005b). Eastin et al. (2005b) recently used flight-level and GPS dropwindsonde data to demonstrate that several of the strongest and most buoyant updrafts in Guillermo's eyewall likely resulted from low-level mixing between eye and eyewall in association mesovortical features (Fig. 2), but were unable to determine any spatial or temporal relationships between the mixing and the enhanced updrafts. No observational study has yet documented the spatial structure and frequency of this mixing, nor the impact of the mixing on the overall modulation of deep convection. **We propose to directly examine the 3D mass transport across the eye-eyewall interface using the multiple dual-Doppler analyses on both days of observation within Guillermo**. Preliminary analysis suggests that the development of deep convective cells is intimately linked to mesovortical-induced outflow from the eye (Fig. 3; Eastin et al. 2004).

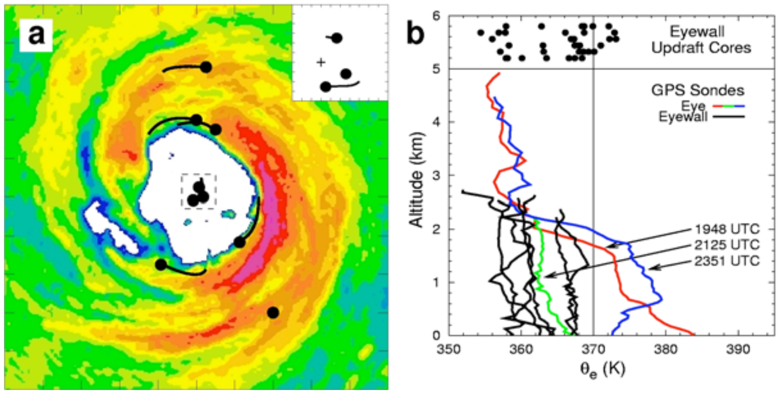

Figure 2. (a) Radar reflectivity at 3 km altitude in Guillermo at 2054 UTC on 3 August. Domain is 120 x 120 km. Superimposed are GPS dropwindsonde launch locations and trajectories. Inset (10 x 10 km) shows trajectories for the eye sondes. (b) Vertical profiles of θ_e and average θ_e within all eyewall updrafts encountered at 5.5 km altitude.

The dual-Doppler investigation of Guillermo is completed with a documentation of the upper-tropospheric wind structure of the vortex. According to observations of R00 and numerical simulations of Frank and Ritchie (2001), it is at upper-levels of the TC where vertical shear first has its detrimental impact on the vortex. In dry idealized TC simulations, Jones (2000) illustrated how the weaker upper-level circulation is more susceptible to vertical shearing, and in many cases is simply advected away from the low-level circulation by the vertical shear flow. Frank and Ritchie (2001) showed that with the development of convective asymmetry in their model, a gradual erosion of the upper-tropospheric vortex ensued. They argued that the dynamical mechanisms which drive the TC towards axisymmetry are unable to counter the negative impacts of convective asymmetry on structure. No observational studies to date have documented the 3D *evolution* of the upper-level TC structure. R00 found that Olivia's precipitation field became so asymmetric on the second day of observation that the upper-tropospheric vortex could not be usefully defined and examined. **The Guillermo dual-Doppler dataset provides a unique opportunity to study the 3D upper-tropospheric vortex evolution of a vertically-sheared TC since scatterers were more or less distributed about the vortex center (Fig. 1)**.

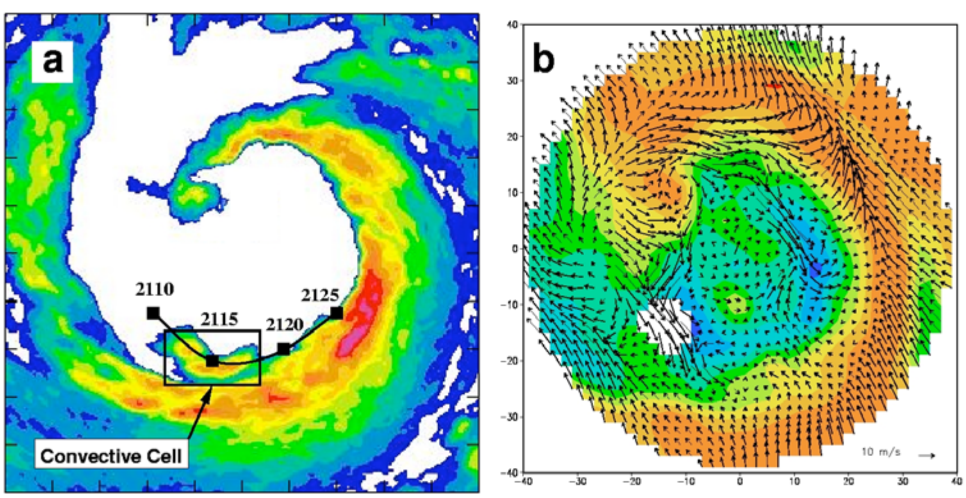

Figure 3. (a) Radar reflectivity within Guillermo at 5.5 km altitude at 2115 UTC on 2 August 1997. Domain is 80 x 80 km. A transient convective cell's locations during the dual-Doppler compositing period are shown. (b) Dual-Doppler derived asymmetric wind vectors and radar reflectivity at 2 km altitude. Note the rough collocation of enhanced outflow associated with an eye-eyewall mesovortex and the transient convective cell.

4.2. Supplementary data sources

Evolution of the inner-core kinematic and convective structure of a TC is intimately linked to the evolution of the thermodynamic structure and large-scale environment. A wide variety of additional data sources will be employed to provide validation, context, and aid in the development of a more complete view of the dynamical processes within a translating, vertically-sheared TC. These data include flight-level and GPS dropwindsonde (Hock and Franklin 1999) observations, radial cross-sections of vertically incident (VI) Doppler data (Black et al. 1996), AVN model analyses (Caplan et al. 1997), and multi-channel satellite imagery (Hawkins et al 2001).

The modulation of eyewall convection through dynamic interaction between the eye and eyewall has yet to be fully understood. Observations (Hawkins and Imbembo 1976; Jorgensen 1984b; Willoughby 1998; Heymsfield et al. 2001; Kossin and Eastin 2001; Eastin et al. 2005b) and numerical simulations (Liu et al. 1999; Braun 2002; Persing and Montgomery 2003) indicate that θ_e in the low-level eye can, at times, exceed θ_e in the eyewall by 5-10 K. As noted previously, Braun (2002), Persing and Montgomery (2003), and Eastin et al. (2005b) suggested that the outward advection this high-θ_e air into the eyewall in association with mesovortices along the eye-eyewall interface can generate locally buoyant updrafts, and thus modulate eyewall convection. The proposed observational study offers a unique opportunity to simultaneously examine the inner-core thermodynamic evolution in conjunction with the 3D wind fields. Copious flight-level and GPS dropwindsonde data will be used to document the thermodynamic structure and evolution. These data will help clarify the temporal and spatial relationships between deep buoyant eyewall convection, low- and high-wavenumber mixing across the eye-eyewall interface, and the depletion of the high-θ_e reservoir in the low-level eye.

The supplementary data is also crucial to the investigation of the quasi-persistent convective asymmetry associated with storm motion and vertical shear. In order to provide validation and a synoptic-scale context for the dual-Doppler derived vertical shear estimates, AVN global model analyses will be used to compute large-scale shear estimates and overall atmospheric structure every 6 h over the duration of the two-day dual-Doppler observation period. Previous comparisons of Doppler-derived and large-scale vertical shear have shown consistency (e.g., Marks et al. 1992). Available GOES and Special Sensor Microwave Imager (SSMI) multichannel imagery will be used to diagnose the gross evolution of inner-core convective structure and vigor during the Doppler observation period. Flight-level penetrations through the convective asymmetry will then be used to provide thermodynamic information on the convective and mesoscale thermal anomaly. Doppler radar VI cross-sections coincident with the thermodynamic data will provide a 2D look at the reflectivity and vertical motion fields within the convective asymmetry from which the distribution of latent heating throughout the troposphere can be deduced. Since VI cross-sections utilize *only* vertically pointing radar beams obtained every 6 s, a relatively high-resolution (temporal and spatial) “snap-shot” of reflectivity and vertical wind can be constructed across typical hurricane convection. These vertical wind measurements are more accurate than that those derived from dual-Doppler analyses where vertical motion is determined by integrating the mass continuity equation.

4.3. Idealized numerical study

The primary focus of the proposed numerical study is on the interaction of the TC with vertical shear flow and the means by which this interaction impacts the vortex structure in a moist convective environment. **The objective is to extend the wave-mean paradigm for TCs in vertical shear (section 2.3), previously developed by RMG04 for dry vortices, to moist convective vortices.** In particular, a parameterization of the quasi-persistent shear-induced asymmetry in eyewall convection is sought within the wave-mean context, motivated by the proposed observational study of Guillermo and other available storms. The impact of internally generated vortex asymmetries on the evolution of vertically sheared TCs (e.g., through the modulation of eyewall convection) will be considered as an auxiliary problem.

In recent literature the idealized numerical study of TCs in vertical shear flow has been approached in two complementary ways. In the first approach the numerical models employ some quasi-realistic representation of moist physical processes, and the vertically-sheared environmental flow is constrained to be a simple time-invariant, often uni-directional, function of height only (Wang and Holland 1996; Bender 1997; Frank and Ritchie 1999, 2001). The environmental flow is usually imposed in these studies after an initial weak vortex has spun-up to hurricane strength. A different approach to the problem has focused exclusively on the intrinsic vortex dynamics of the TC in shear by neglecting both moist processes and interactions with the frictional boundary layer (Jones 1995, 2000, 2004; DeMaria 1996; Smith et al. 2000; RMG04). The initial TC is prescribed, and then forced by a simple vertical shear flow. While the former approach is more likely to yield a TC evolution that mimics nature in detail, our intent here is to isolate basic mechanisms involved in the resiliency or susceptibility of TC-like vortices to vertical shearing. Hence, we are guided by the latter approach.

To isolate the impact of axisymmetric latent heating on TC resiliency in vertical shear, we propose a series of numerical simulations in which convective asymmetry is prohibited. A linearized nonhydrostatic model with both axisymmetric heat forcing and environmental vertical shear is employed. Flatau et al. (1994) considered the nonlinear analog of this problem, but focused primarily on the motion of baroclinic TCs. The linearized formulation proposed here allows us to directly examine the tilt evolution of the TC with parameterized axisymmetric latent heating within the VRW framework of RMG04. RMG04 argued that mechanisms intrinsic to the dry dynamics are fundamentally responsible for the *resiliency* of the TC in vertical shear through a series of dry numerical simulations. This testable hypothesis does not encompass the complete evolution of the TC in vertical shear, but rather suggests that when one considers only what keeps the vortex upright, mechanisms identified in the dry dynamical context likely explain vortex robustness more generally. Conceptually, the extrapolation of the dry resiliency theory to the moist regime is based upon the finding that in regions of saturated ascent static stability is reduced (Durran and Klemp 1982). According to RMG04, the VRW alignment mechanism is more efficient for weaker static stability. It is therefore expected that the presence of symmetric heating will yield a more resilient vortex than in the case without heating, but it is currently unknown to what extent the basic dynamical mechanisms responsible for the resiliency are similar to those in the dry model.

Mesoscale ascent forced by the interaction of the TC with ambient vertical shear flow will also impact latent heating within the saturated vortex core, but in an asymmetric manner, oriented relative to the vertical shear vector. We assume here that latent heating is directly proportional to the asymmetric vertical motion, the so-called "effective stratification" approach (e.g., Emanuel et al. 1987). Patra (2004) recently utilized this approach in modeling the asymmetric heating response of the TC in vertical shear. The primitive equations used for saturated flow are formally identical to the dry adiabatic primitive equations, but with the Brunt-Väisälä frequency in the thermodynamic equation replaced by a reduced moist Brunt-Väisälä frequency,

$$N_m^2 = \frac{g}{\theta_o}\left(\frac{\partial \theta}{\partial z} - \gamma\right),$$

where g is the gravitational constant, θ_o a reference value of potential temperature, and γ a proportionality factor between heating and vertical velocity at each gridpoint. A similar approach is taken here, but within the framework of the linearized nonhydrostatic model. The axisymmetric heat forcing is set to zero so that modification of the axisymmetric flow occurs solely through wave-mean interactions. It is important to note that when the effective stratification is reduced uniformly across the domain, the intrinsically dry dynamical mechanism of RMG04 should completely explain the TC evolution in vertical shear. **Therefore, the focus of the proposed study of the vertically-sheared TC with asymmetric saturated mesoscale ascent is on the impact of spatial inhomogeneities in effective stratification on the vortex evolution.** Observations described in sections 4.1 and 4.2 will be used to define the effective stratification. The VRW wave-mean dynamics of the TC in vertical shear will then be examined using the realistic radial and vertical distributions of effective stratification. According to RMG04, as the effective stratification approaches the moist neutral limit within the vortex core, the nature of the vortex alignment mechanism changes; the VRW core mode ceases to exist, and alignment occurs through the projection of the vortex tilt asymmetry onto sheared VRWs. RMG04 did not examine the *vertically-sheared* TC in this limit. **An outstanding question we will address is whether the VRW core mode can exist in the presence of saturated mesoscale ascent within the eyewall, and if not, to what extent the sheared VRW dynamics explains TC resiliency.**

Superimposed upon the aforementioned mesoscale ascent are isolated convective cells (e.g., Fig. 3). Anecdotal evidence from "full-physics" numerical simulations (e.g., Frank and Ritchie 2001) suggests that asymmetric deep cumulus convection precedes the top-down weakening of vertically-sheared TCs. **We propose to utilize observations of the convective asymmetry observed within Hurricane Guillermo (1997) to motivate idealized numerical simulations exploring the impact of convective asymmetry on the TC in vertical shear.** When the TC is vertically sheared, convective cells form predominantly downshear and to the left of shear (Black et al. 2002; Eastin et al. 2005b). No simple relation exists between the vertical shearing of a TC and the timing, structure, and intensity of these convective cells. The convective cells first will be represented using a time-dependent asymmetric heat source located downshear. The dry-dynamical core of an existing mesoscale numerical model will be used to simulate the vertically-sheared vortex since the imposed heat forcing is expected to produce asymmetry amplitudes beyond the formal validity of the linearized model. We anticipate that one of the consequences of persistent convective asymmetry downshear is the persistent, but pulsated, generation of 3D (potential) vorticity anomalies within the eyewall. **The mesoscale numerical model will also be used to simulate the evolution of a TC-like vortex under the influence of simultaneous vertical shear forcing and downshear vorticity pulsing.** Observations of Guillermo's asymmetric vorticity structure and evolution will provide guidance in the construction of the vorticity forcing. The pulsing of thermal anomalies may also be incorporated, as suggested in Nolan and Grasso (2003), or some combination of thermal and vortical perturbations.

A significant difference between the proposed research and previous studies of the wave-mean TC interaction is the fact that here we must consider the impact of VRWs generated simultaneously by the vertical shearing of the vortex and the diabatic response to vertical shearing. Towards this end we will return to the linearized nonhydrostatic model to help elucidate basic mechanisms involved in the interaction of the vertically-sheared TC vortex with the shear-modulated convective asymmetry. Although stated above that we expect asymmetry amplitudes to generally exceed values appropriate for formal validity of the linear model, we follow previous studies of the free-evolution of convectively-generated asymmetries within TC-like vortices and focus on basic insight rather than quantitative accuracy. The wave-mean approach, which has been used previously to predict the zeroth-order impact of convectively-generated VRWs on the axisymmetric TC vortex, is a natural one here since it encompasses to some degree both the vortex tilt evolution (e.g., RMG04) and vortex-convection interaction. As an example, we propose to use the wave-mean approach to examine the impact of convectively-generated upper-level negative potential vorticity anomalies on the vertically-sheared TC vortex. Another potential impact of asymmetric convective heating to be exploited by the wave-mean approach is the interaction between convectively-forced VRW core modes and the vertical shear forcing (note: it is possible to construct a diabatic heating in the linear model of RMG04 that has the same impact on potential vorticity as a vertical shear forcing in terms of the generation of tilt asymmetry). While this latter impact is purely speculative, it emphasizes the fact that the VRW paradigm for TC resiliency is easily extended to include the convective aspects of the problem.

Vortex asymmetries generated through internal processes within the TC core will be examined here in terms of their capacity to modulate deep cumulus convection within the eyewall. Recently Braun (2002) documented the triggering of convective cells in conjunction with vortical features within the eyewall of a numerically simulated storm. New cells formed in regions of enhanced convergence associated with the superposition of the environmental flow and vortical asymmetries in the eyewall. R00 and Black et al. (2002) observed a similar modulation of convection within the eyewall of Hurricane Olivia (1994). How this modulation of the quasi-persistent convective asymmetry associated with vertical shear (and storm motion) impacts the overall evolution of storm structure is not known. The internal modulation will be included in the nonlinear simulations through the use of dynamically unstable initial vortex profiles (e.g., Nolan and Montgomery 2002).

4.4. Plan of research

The plan of research has been divided into three steps. The first step involves the 3D documentation of a TC's low-azimuthal wavenumber and convective structure using multiple dual-Doppler analyses. The second step assimilates additional data sources to provide a more complete convective and large-scale picture of the TC evolution. The third step utilizes idealized numerical simulations to further investigate the positive and negative roles of moist convection on the evolution of vertically-sheared TCs, and the fundamental dynamical processes that impact the spatial and temporal distribution of eyewall convection.

4.4.1. Step 1. Doppler analysis of a TC's low-wavenumber and convective structure

In order to document the axisymmetric and asymmetric components of the TC flow, and to obtain insight into the dynamics governing the evolution of these components, an azimuthal Fourier decomposition of each unique dual-Doppler wind composite must be performed. Our analysis will follow procedures similar to those outlined by R00. First, the raw Doppler sweep data will be edited using NCAR's interactive SOLO software (Oye et al. 1995). Next, 3D dual-Doppler wind fields will be constructed using the variational method described by Gamache (1998). Both PIs, Reasor and Eastin, gained expertise editing and analyzing airborne Doppler data using these methods during separate post-doctoral appointments at NOAA's HRD. Drs. Frank Marks and John Gamache of HRD have offered their assistance in this phase of the observational study, and in the subsequent analysis.

After mapping the 3D wind data into a storm-relative cylindrical coordinate system, a simplex algorithm will be employed to identify the center that maximizes the axisymmetric component of the tangential winds within an annulus centered on the eyewall (Neldar and Mead 1965; Marks et al. 1992). The simplex method is used to minimize the asymmetry due to vortex center mislocation. An alternative center-finding method that locates the vorticity centroid (Jones 2004) will also be tested. The newly defined centers at each level, which also provide a measure of vortex tilt, will then be used to compute the domain mean wind at each level, from which a reasonable estimate of the local vertical shear is obtained (Marks et al. 1992; R00). The new centers are also employed in the azimuthal wavenumber decomposition.

Once each 3D wind composite is decomposed, the evolution of the axisymmetric and asymmetric low-wavenumber components (wavenumbers one to four) will be documented in conjunction with the convective structure. The symmetric evolution during both rapid intensification and steady-state periods will be examined using an axisymmetric tangential wind budget (e.g., R00) and compared to idealized numerical simulations discussed below. The asymmetric wavenumbers will be analyzed separately, with particular emphasis on the evolution of the vertical vorticity. We will then catalogue the magnitude and 3D structure of the lowest-wavenumbers for each dual-Doppler analysis. The phase of the wavenumber components will be compared to the orientation of the vertical shear vector, the vortex tilt vector, and any deep convective asymmetries. We will combine these statistics to characterize the evolution of the 3D asymmetric vertical vorticity, and infer spatial and temporal relationships between the asymmetric flow and enhanced convective asymmetries. Furthermore, these statistics will be analyzed in combination with animated radar reflectivity fields from each aircraft's lower-fuselage radar to provide estimates of azimuthal and radial propagation speeds for each wavenumber. These observed propagation speeds will be compared to expectations from linear VRW theory (Montgomery and Kallenbach 1997). Both the axisymmetric and asymmetric analyses will undoubtedly benefit from the unprecedented wind field coverage within the eye. Through such comprehensive observational analysis, we hope to provide the most complete 3D documentation of a rapidly intensifying and steady-state TC core to date, and clarify the impact of evolving asymmetric structures on the spatial distribution of convection in the TC core.

The unprecedented wind field coverage throughout the eye provides an opportunity to observationally document the evolution of mass exchange between the eye and eyewall. In addition to the low-wavenumber analysis previously described, a census of numerous air parcel trajectories will be performed. Hundreds (if not thousands) of passive tracers will be introduced into the eye and eyewall volumes and then advected by the dual-Doppler wind fields following the methods outlined by Marks et al. (1992). After definition of the eye-eyewall interface (e.g., a specified radius or radar reflectivity value; both will be evaluated), the extent of 3D mass transport across the interface can be estimated from the number of crossing trajectories and their frequency as a function of altitude. Through comparison with the low-wavenumber analysis, the dominant spatial scales accomplishing the transport can be inferred as well as the source region of any air entering eyewall updrafts. Trajectories will be evaluated for each unique dual-Doppler analysis separately, under the assumption that the wind field remains in steady state. Differences in mixing statistics between Doppler analyses will provide information on the evolution of such mixing and its relation to TC intensity change. Clearly, the census statistics developed here will provide important information regarding the dominant spatial and temporal scales of such mixing and insight into the generation and enhancement of eyewall convection via such a process.

4.4.2. *Step 2. Assimilation of other data sources*

To complement the 3D kinematic and convective analyses, additional data pertaining to the inner-core thermodynamic structure and the large-scale environment will be assimilated. These data will provide validation and context for the Doppler analysis results, as well as initial conditions for the numerical simulations.

First, inner-core thermodynamic structure and evolution will be derived from both flight-level and GPS dropsonde data preprocessed at NOAA's HRD (Willoughby et al. 1982; Samsury and Zipser 1995; Hock and Franklin 1999). Flight-level observations were collected both days in each quadrant at 3.0 and 5.5 km altitude, but only the data at 5.5 km could be further processed following Eastin et al. (2002a) to effectively remove instrument wetting errors, and thus be used to reliably diagnose thermodynamic characteristics of convection (e.g., θ_e and buoyancy). A total of 87 GPS dropsondes were launched in Guillermo. In particular, nine dropsondes were deployed in the eye (three on 2 August and six on 3 August) near the circulation center and nine in the eyewall (all on 3 August). These data will help clarify spatial and temporal relationships between deep buoyant eyewall convection, low-wavenumber mixing across the eye-eyewall interface, and the evolution of gross thermodynamic structure.

Second, evolution of the large-scale environmental structure throughout the four day period encompassing the two inner-core observation periods on 2 and 3 August will be diagnosed from gridded AVN model analyses available every 6 h at 1° resolution. In particular, estimates of environmental vertical wind shear as well as potential vorticity, moist static stability, divergence, and the flux convergence of eddy angular momentum will be calculated (e.g., DeMaria and Kaplan 1994; Molinari et al. 1995). Available GOES and Special Sensor Microwave Imager

(SSMI) multichannel imagery will also be used to diagnose the gross inner-core convective structure and vigor during the same four day period. Sea surface temperatures will be derived from weekly analyses (Reynolds and Smith 1993) since no direct measurements are available. This data will help place the more detailed dual-Doppler analysis of vertical shear, convective asymmetry, and vortex tilt evolution within a large-scale synoptic context. Furthermore, this data will help clarify the relative significance of convective modulation by the internal dynamics compared to that by external forcing with regards to their impact on TC intensity.

Finally, in order to provide the most realistic representation of asymmetric convection for use in the idealized numerical simulations, a statistical analysis of the flight-level, dropsonde, and VI Doppler data will be combined with statistics derived from the dual-Doppler analyses. In cooperation with Michael Black at HRD, a total of 24 radial VI cross-sections were made available. The cross-sections, which are evenly distributed around the storm center, provide along-track vertical profiles of vertical air velocity and radar reflectivity (Black et al. 1996). The VI (and dual-Doppler) analyses can be used to provide a statistical representation of vertical velocity and latent heating throughout the troposphere, while statistical estimates of vertical stability and local buoyancy can be derived from the dropsonde and flight-level data. These collective statistics, combined with a few plausible assumptions, will provide more realistic vertical profiles of convective heating (and thus convectively-induced sources and sinks of potential vorticity), including its azimuthal distribution.

4.4.3. *Step 3. Numerical simulations*

The numerical simulations will be carried out using three models of increasing complexity: 1) a hydrostatic, linearized equivalent barotropic primitive equation model, 2) a nonhydrostatic, linearized 3D primitive equation model, and 3) the Weather Research and Forecasting (WRF) model (Michalakes et al. 2001). As discussed in section 4.3, the purpose of the simulations is to aid interpretation of the observational case studies and to provide basic insight into the role of externally and internally forced convective asymmetry in TC structure change. The basic simulations were discussed in section 4.3, so here we focus on the models to be used.

The linear equivalent barotropic model is described by RMG04. The axisymmetric vortex is assumed barotropic. The vortex tilt is represented by an azimuthal wavenumber one baroclinic mode, or is generated through a time-invariant vertical shear forcing of similar vertical structure. We propose to add diabatic heating to the linearized thermodynamic equation in two ways: 1) as an arbitrary heat source and 2) as a heating proportional to vertical velocity (i.e., a moist Brunt-Väisälä frequency). This model provides a simple testbed for examining how the VRW resiliency mechanism is modified by arbitrary asymmetric heating, or heating directly tied to the asymmetric mesoscale ascent associated with the vortex-shear interaction. Specific simulations will be carried out to document the conditions under which the VRW core mode ceases to exist, and the ensuing role of diabatically-modified sheared VRWs in the vertically-sheared vortex evolution.

The nonhydrostatic, linearized 3D primitive equation model has been provided by Dr. David Nolan of the University of Miami, and is documented in Nolan and Montgomery (2002) and Nolan and Grasso (2003). The model is based on the anelastic equations of motion, linearized about an axisymmetric vortex in gradient and hydrostatic balance. As originally formulated, the axisymmetric fields remain unchanged, but axisymmetric tendencies are evaluated in association with eddy flux divergences and axisymmetric heating. We propose to add asymmetric heating and vertical shear forcing to the asymmetry equations. The addition of a steady vertical shear forcing in geostrophic balance follows RMG04 for the linearized equivalent barotropic model. A "wave-mean" model is developed using eddy flux divergences derived from the asymmetry equations. The eddy forcing generates a tendency in the axisymmetric fields, which is then used to update the axisymmetric vortex for the next timestep of the asymmetry equations.

In the experiments with steady axisymmetric heating, the asymmetries are not permitted to impact the axisymmetric vortex, but the evolving axisymmetric vortex with secondary circulation is permitted to impact the evolution of the shear-generated asymmetries (through an update of the axisymmetric fields in the asymmetry equations). In the experiments without axisymmetric heating and with asymmetric latent heating due to shear-induced moist ascent, only the asymmetry equations are solved. The vertical gradient of axisymmetric potential temperature is replaced by an effective stratification in the thermodynamic equation (e.g., Emanuel et al. 1987). The height coordinate form of the effective stratification for saturated ascent is:

$$\frac{\Gamma_m}{\Gamma_d}\frac{\overline{\theta}}{\overline{\theta}_{es}}\frac{\partial\overline{\theta}_{es}}{\partial z},$$

where Γ_m and Γ_d are the moist and dry adiabatic lapse rates, respectively, and $\overline{\theta}_{es}$ is the axisymmetric saturated equivalent potential temperature. Thermodynamic quantities from flight-level and GPS dropwindsonde measurements taken throughout the core of Hurricane Guillermo (1997) on both days of observation will be used to construct the 3D structure of effective stratification for use in the numerical simulations.

The impact of convective asymmetry on the vertically-sheared TC evolution is investigated first using the dry "dynamical core" of the WRF model. The height coordinate form of WRF (version 1.3) is initialized with an axisymmetric vortex in gradient and hydrostatic balance. Since the axisymmetric secondary circulation is not being simulated here, no boundary layer scheme is employed. A time-dependent asymmetric heat forcing is included within the downshear quadrant of the TC eyewall. In a subsequent set of experiments, the heat forcing is replaced by periodically introduced balanced potential vorticity asymmetries. To complete the investigation of the convective asymmetry we will compare the vortex evolution from the WRF model with asymmetric convective heating (or vorticity pulsing) to the wave-mean model predictions with similar initial conditions. The goal is to determine whether the top-down weakening of an initially axisymmetric TC in vertical shear can be captured with mesoscale representations of convective asymmetry and, if so, explain the dynamical mechanisms.

5. Management plan

The collaborative nature of this proposal was borne out of the co-PI's sequential, but non-overlapping, tenures at HRD. A common interest in the Guillermo dataset developed, with Dr. Eastin focused on the internal modulation of eyewall convection and Dr. Reasor focused on the external modulation of convection. It was determined that these complementary, and inevitably intertwined, foci were best addressed in a singular effort. In their preliminary examination of the radar data at different institutions, the co-PIs have already demonstrated the feasibility of this collaborative approach. The combined expertise is absolutely necessary for the success of the project.

Dr. Reasor will provide overall leadership and guidance for the project, ensuring that interaction between the co-PIs, graduate students, undergraduate students, and unfunded collaborators is conducted regularly. The roles played by each co-PI are designed to capitalize upon their strengths and background. Dr. Reasor, with the help of two graduate students, will conduct the numerical simulations and the observational analyses associated with external forcing and TC resiliency. Dr. Eastin, with the help of one undergraduate student, will conduct the observational analyses of the TC's low-wavenumber structure and evolution, including its impact on the distribution of TC convection. Dr. Nolan (University of Miami) will assist with the nonhydrostatic linearized numerical simulations as an unfunded collaborator. Findings of the observational analyses will be used to define and initialize the numerical simulations. The co-PIs and students will jointly edit the radar data and generate the dual-Doppler analyses. Drs. Reasor, Eastin, and Nolan are currently in regular contact via telephone and email. Two trips a year are planned for the co-PIs to interact with each other, as well as with HRD scientists. We anticipate no difficulty in communications regarding different aspects of this proposed research.

6. Summary of Broader Impacts

The proposed activities will have several broader impacts. Regarding hurricanes: Presently, there exists a single observational study of the three-dimensional hurricane vorticity dynamics. The proposed case study is an important step towards increasing the statistical database of three-dimensional observations, which is crucial if such data are to be meaningfully assimilated into mesoscale numerical forecast models. Additionally, the proposed mapping of effective stratification based on observed data within the hurricane core may be used by future investigators for idealized numerical modeling. More generally: The convection-vortex interaction is a general atmospheric problem (e.g., mid-latitude MCVs) and has parallels with the convectively-coupled equatorial wave problem. The proposed study draws upon this broader knowledge base, and in return will contribute beyond the scope of hurricanes. Two graduate students and an undergraduate will be trained in the techniques of radar data editing and analysis, atmospheric dynamics, and numerical modeling. These students will also be encouraged to interact with scientists at NOAA's Hurricane Research Division through their ongoing cooperation with the universities.

7. Results from prior NSF support

A theoretical and observational study of midlatitude mesoscale convective vortices (MCVs) in vertical shear, *NSF Grant* ATM-0305412
April 15, 2003– April 15, 200 $429K PI: M. T. Montgomery Co-PI: P. D. Reasor (no salary support)

This study is in support of the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) that took place from 20 May to 6 July 2003. Prior to BAMEX, only sparse observations of the wind structure of midlatitude MCVs existed. The co-PI (Reasor) has completed analysis of airborne dual-Doppler observations of an MCV during IOP1 of BAMEX. The MCV developed through an apparent series of vortex mergers prior to the observation period. Two consecutive 3D Doppler wind composites through the core of the resulting mature MCV indicate little downward extension of the mid-level vortex, consistent with observations of strong vertical shear in the surface- to 3-km layer. Shallow convection near the vortex center was evidently insufficient to maintain the vortex much beyond the observation period. The observations support the idea that the retriggering of convection (which is strongly correlated with MCV longevity) requires the interaction of some low-level ambient vertical shear with the downward-penetrating MCV circulation. If the shear is so strong as to tear apart the low-level MCV circulation, the retriggering mechanism (e.g., Raymond and Jiang 1990) is ineffective. Documentation of the larger-scale vortex structure through a composite of all Doppler data in and around the IOP1 MCV is currently underway. The goal is to use the observed 3D vortex structure to motivate idealized simulations exploring why this MCV apparently succumbed to the low-level vertical shear.

Recent Conference Proceedings :

Reasor, P. D., M. T. Montgomery, and M. M. Bell, 2004: Doppler observations of MCV structure during BAMEX IOP 1. *22nd Conference on Severe Local Storms*, Hyannis, MA, Amer. Met. Soc., http://ams.confex.com/ams/11aram22sls/techprogram/paper_82168.htm

References Cited

Bender, M. A., 1997: The effect of relative flow on the asymmetric structure in the interior of hurricanes. *J. Atmos. Sci.*, **49**, 703-724.

Black, M. L., R. W. Burpee, and F. D. Marks Jr., 1996: Vertical motion characteristics of tropical cyclones determined with airborne Doppler radial velocities. *J. Atmos. Sci.*, **53**, 1887-1909.

Black, M. L., J. F. Gamache, F. D. Marks, Jr., C. E. Samsury, and H. E. Willoughby, 2002: Eastern Pacific Hurricanes Jimena of 1991 and Olivia of 1994: The effect of vertical shear on structure and intensity. *Mon. Wea. Rev.*, **130**, 2291-2312.

Braun, S. A., 2002: A cloud-resolving simulation of Hurricane Bob (1991): Storm structure and eyewall buoyancy. *Mon. Wea. Rev.*, **130**, 1573-1592.

Caplan, P., J. Derber, W. Gemmill, S.-Y. Hong, H.-L. Pan, and D. Parrish, 1997: Changes to the 1995 NCEP operational Medium-Range Forecast model analysis-forecast system. *Wea. Forecasting*, **12**, 581-594.

Corbosiero, K. L., and J. Molinari, 2003: The relationship between storm motion, vertical wind shear, and convective asymmetries in tropical cyclones. *J. Atmos. Sci.*, **60**, 366-376.

DeMaria, M., and J. Kaplan, 1994: A statistical hurricane intensity prediction scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **10**, 433-446.

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.*, **53**, 2076-2087.

DeMaria, M., and J. Kaplan, 1999: An updated Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic and Eastern North Pacific basins. *Wea. Forecasting*, **14**, 326-337.

Dodge, P., R. W. Burpee, and F. D. Marks, Jr., 1999: The kinematic structure of a hurricane with sea level pressure less than 900 mb. *Mon. Wea. Rev.*, **127**, 987-1004.

Durran, D. R, and J. B. Klemp, 1982: On the effects of moisture on the Brunt-Väisälä frequency. *J. Atmos. Sci.*, **39**, 2152–2158.

Eastin, M. D., P. G. Black, and W. M. Gray, 2002a: Flight-level instrument wetting errors in hurricanes. Part I: Observations. *Mon. Wea. Rev.*, **130**, 825-841.

Eastin, M. D., P. G. Black, and W. M. Gray, 2002b: Flight-level instrument wetting errors in hurricanes. Part II: Implications. *Mon. Wea. Rev.*, **130**, 842-851.

Eastin, M. D., W. M. Gray, and P. G. Black, 2005a: Buoyancy of convective vertical motions in the inner core of intense hurricanes. Part I: General statistics. *Mon. Wea. Rev.*, in press.

Eastin, M. D., W. M. Gray, and P. G. Black, 2005b: Buoyancy of convective vertical motions in the inner core of intense hurricanes. Part II: Case studies. *Mon. Wea. Rev.*, in press.

Eastin, M. D., P. D. Reasor, J. F. Gamache, F. D. Marks Jr., and M. L. Black, 2004: Observed evolution of eyewall convection and low-wavenumber flow in Hurricane Guillermo (1997). Preprints, *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 445-446.

Elsberry, R. L., G. H. Holland, H. Garrish, M. DeMaria, and C. P. Guard, 1999: Is there any there any hope for tropical cyclone intensity change prediction? – A panel discussion. *Bull. Amer. Meteor. Soc.*, **73**, 264-275.

Emanuel, K. A., M. Fantini, and A. J. Thorpe, 1987: Baroclinic instability in an environment of small stability to slantwise moist convection. Part I: Two-dimensional models. *J. Atmos. Sci*., **44**, 1559-1573.

Flatau, M., W. H. Schubert, and D. E. Stevens, 1994: The role of baroclinic processes in tropical cyclone motion: the influence of vertical tilt. *J. Atmos. Sci.*, **51**, 2589-2601.

Frank , W. M., and E. A. Ritchie, 1999: Effects of environmental flow upon tropical cyclone structure. *Mon. Wea. Rev*., **127**, 2044-2061.

Frank , W. M., and E. A. Ritchie, 2001: Effects of vertical shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev*., **129**, 2249-2269.

Gamache, J. F., 1998: Evaluation of a fully three-dimensional variational Doppler analysis technique. Preprints, *28th Conf. on Radar Meteorology*, Austin, TX, Amer. Meteor. Soc., 422-423.

Gamache, J. L., J. S. Griffin, P. P. Dodge, and N. F. Griffin, 2004: Automatic Doppler analysis of three-dimensional wind fields in hurricane eyewalls. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 164-165.

Hawkins, H. F., and S. M. Imbembo, 1976: The structure of a small, intense hurricane – Inez 1966. *Mon. Wea. Rev*., **104**, 418-422.

Hawkins, J. D., T. F. Lee, J. Turk, C. Sampson, J. Kent, and K. Richardson, 2001: Real-time distribution of satellite products for tropical cyclone reconnaissance. *Bull. Amer. Meteor. Soc.*, **82**, 567-578.

Heymsfield, G. M., J. B. Halverson, J. Simpson, L. Tian, and T. P. Bui, 2001: ER-2 Doppler radar investigations of the eyewall of Hurricane Bonnie during the Convection and Moisture Experiment-3. *J. Appl. Meteor*., **40**, 1310-1330.

Hock, T. F., and J. L. Franklin, 1999: The NCAR GPS dropwindsonde. *Bull. Amer. Meteor. Soc*., **80**, 407-420.

Jones, S. C., 1995: The evolution of vortices in vertical shear. Part II: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc*., **121**, 821-851.

Jones, S. C., 2000: The evolution of vortices in vertical shear. Part III: Baroclinic vortices. *Quart. J. Roy. Meteor. Soc*., **126**, 3161-3185.

Jones, S. C., 2004: On the ability of dry tropical-cyclone-like vortices to withstand vertical shear. *J. Atmos. Sci*., **61**, 114-119.

Jorgensen, D. P., 1984a: Mesoscale and convective-scale characteristics of mature hurricanes. Part I: General observations by research aircraft. *J. Atmos. Sci.*, **41**, 1268-1285.

Jorgensen, D. P., 1984b: Mesoscale and convective-scale characteristics of mature hurricanes. Part II: Inner core of Hurricane Allen (1980). *J. Atmos. Sci.*, **41**, 1287-1311.

Kossin, J. P., and M. D. Eastin, 2001: Two distinct regimes in the kinematic and thermodynamic structure of the hurricane eye and eyewall. *J. Atmos. Sci.*, **58**, 1079-1090.

Kuo, H.-C., R. T. Williams, and J.-H. Chen, 1999: A possible mechanism for the eye rotation of Typhoon Herb. *J. Atmos. Sci.*, **56**, 1659-1673.

La Seur, N. E., and H. F. Hawkins, 1963: An analysis of Hurricane Cleo (1958) based on data from research reconnaissance aircraft. *Mon. Wea. Rev.*, **91**, 694-709.

Lewis, B. M., and H. F. Hawkins, 1982: Polygonal eye walls and rainbands in hurricanes. *Bull. Amer. Meteor. Soc.*, **63**, 1294-1300.

Liu, Y., D. L. Zhang, and M. K. Yau, 1999: A multiscale numerical study of Hurricane Andrew (1992). Part II: Kinematics and inner core structure. *Mon. Wea. Rev.*, **127**, 2597-2616.

Malkus, J. S., 1958: On the structure and maintenance of the mature hurricane eye. *J. Meteor.*, **15**, 337-349.

Marks, F. D., Jr., and R. A. Houze, Jr., 1984: Airborne Doppler radar observations in Hurricane Debby. *Bull. Amer. Meteor. Soc.*, **65**, 569-582.

Marks, F. D., Jr., and R. A. Houze, Jr., 1987: Inner core structure of Hurricane Alicia from airborne Doppler radar observations. *J. Atmos. Sci.*, **44**, 1296-1317.

Marks, F. D., R. A. Houze, and J. Gamache, 1992: Dual-aircraft investigation of the inner core of Hurricane Norbert. Part I: Kinematic structure. *J. Atmos.Sci.*, **49**, 919-942.

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock, 2001: Design of the next generation weather research and forecast model. *Development in Tera-Computing: Proceeding for the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology,* W. Zwieflholder and N. Kreitz, eds., World Scientific, 269-276.

Molinari, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy momentum fluxes. *J. Atmos. Sci.*, **49**, 1093-1105.

Molinari, J., S. Skubis, and D. Vollaro, 1995: External influences on hurricane intensity. Part III: Potential vorticity structure. *J. Atmos. Sci.*, **52**, 3593-3606.

Möller, J. D., and M. T. Montgomery, 1999: Vortex Rossby waves and hurricane intensification in a barotropic model. *J. Atmos. Sci.*, **56**, 1674-1687.

Möller, J. D., and M. T. Montgomery, 2000: Tropical cyclone evolution via potential vorticity anomalies in a three-dimensional balance model. *J. Atmos. Sci.*, **57**, 3366-3387.

Montgomery, M. T., and J. Enagonio, 1998: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci.*, **55**, 3176-3207.

Montgomery, M. T., and R. Kallenbach, 1997: A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **123**, 435-465.

Muramatsu, T., 1986: The structure of polygonal eye of a typhoon. *J. Meteor, Soc. Japan*, **64**, 913-921.

Neldar, J. A., and R. Mead, 1965: A simplex method for function minimization. *Comput. J.*, **7**, 308-313.

Nolan, D. S., and L. D. Grasso, 2003: Nonhydrostatic, three-dimensional perturbations to balanced, hurricane-like vortices. Part II: Symmetric response and nonlinear simulations. *J. Atmos. Sci.*, **60**, 2717-2745.

Nolan, D. S., and M. T. Montgomery, 2002: Nonhydrostatic, three-dimensional perturbations to balanced, hurricane-like vortices. Part I: Linearized formulation, stability, and evolution. *J. Atmos. Sci.*, **59**, 2989-3020.

Ooyama, K. 1969: Numerical simulation of the life cycle of tropical cyclones. *J. Atmos. Sci.*, **55**, 3176-3207.

Oye, R., C. Mueller, and S. Smith, 1995: Software for radar translation, visualization, editing, and interpolation. Preprints, *27th Conf. on Radar Meteorology,* Vail, CO, Amer. Meteor. Soc., 359-161.

Patra, R., 2004: Idealized modeling of tropical cyclones in vertical shear: The role of saturated ascent in the inner core. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 98-99.

Persing, J., and M. T. Montgomery, 2003: Hurricane superintensity. *J. Atmos. Sci.*, **60**, 2349-2371.

Raymond, D. J., and H. Jiang, 1990: A theory for long-lived mesoscale convective systems. *J. Atmos. Sci*., **47**, 3067-3077.

Reasor, P. D., M. T. Montgomery, and L. D. Grasso, 2004: A new look at the problem of tropical cyclones in vertical shear flow: Vortex resiliency. *J. Atmos. Sci.*, **61**, 3-22.

Reasor, P. D., M. T. Montgomery, F. D. Marks Jr., and J. F. Gamache, 2000: Low-wavenumber structure and evolution of the hurricane inner core observed by airborne dual-Doppler radar. *Mon. Wea. Rev.*, **128**, 1653-1680.

Reynolds, R. W., and T. M. Smith, 1993: An improved real-time global sea surface temperature analysis. *J. Climate*, **6**, 114-119.

Riehl, H., and J. Malkus, 1961: Some aspects of Hurricane Daisy, 1958. *Tellus*, **13**, 181-213.

Rotunno, R. and K. A. Emanuel, 1987: An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic numerical model. *J. Atmos. Sci.*, **44**, 542-561.

Samsury, C. E., and E. J. Zipser, 1995: Secondary wind maxima in hurricanes: Airflow and relationship to rainbands. *Mon. Wea. Rev.*, **123**, 3502-3517.

Schecter, D. A., and M. T. Montgomery, 2003: On the symmetrization rate of an intense geophysical vortex. *Dyn. Atmos. Oceans*, **37**, 55-88.

Schecter, D. A., M. T. Montgomery, and P. D. Reasor, 2002: A theory for the vertical alignment of a quasigeostrophic vortex. *J. Atmos. Sci*., **59**, 150-168.

Schubert, W. H., J. J. Hack, P. L. Silva Dias, and S. R. Fulton, 1980: Geostrophic adjustment in an axisymmetric vortex. *J. Atmos. Sci*., **37**, 1464-1484.

Schubert, W. H., M. T. Montgomery, R. K. Taft, T. A. Guinn, S. R. Fulton, J. P. Kossin, and J. P. Edwards, 1999: Polygonal eyewalls, asymmetric eye contraction and potential vorticity mixing in hurricanes. *J. Atmos. Sci.*, **56**, 1197-1223.

Shapiro, L. J., 1983: Asymmetric boundary layer flow under a translating hurricane. *J. Atmos. Sci.*, **40**, 1984-1998.

Shapiro, L. J., 2000: Potential vorticity asymmetries and tropical cyclone evolution in a moist three-layer model. *J. Atmos. Sci.*, **57**, 3645-3662.

Smith, R. K., W. Ulrich, and G. Sneddon, 2000: On the dynamics of hurricane-like vortices in vertical shear flows. *Quart. J. Roy. Meteor. Soc*., **126**, 2653-2670.

Wang, Y., and G. J. Holland, 1996: Tropical cyclone motion and evolution in vertical shear. *J. Atmos. Sci.,* **53**, 3313-3332.

Willoughby, H. E., 1990: Temporal changes of the primary circulation in tropical cyclones. *J. Atmos. Sci.*, **47**, 242-264.

Willoughby, H. E., 1998: Tropical cyclone eye thermodynamics. *Mon. Wea. Rev.*, **126**, 3053-3067.

Willoughby, H. E., J. A. Clos, and M. G. Shoreibah, 1982: Concentric eyewalls, secondary wind maxima, and the evolution of the hurricane vortex. *J. Atmos. Sci.*, **33**, 1387 -1402.