# 1.6 FORMATION OF THE HURRICANE EYE

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## 1. Introduction

A plethora of genesis mechanisms result in tropical cyclone formation. Gray (1998b) purports that *hundreds* of tropical cyclogenesis theories have been put forward. Some formation mechanisms (or influences) include low level wind surges (Gray, 1993), barotropic breakdowns of the Intertropical Convergence Zone (Ferreira and Schubert, 1997), Madden-Julian Oscillation twins (Ferreira et al., 1996), upscale vorticity and energy cascade from mesovortex "hot towers" (Hendricks et al., 2004), eddy fluxes of angular momentum and heat from environmental asymmetries (Pfeffer and Challa 1992), development via convectively-forced Vortex Rossby Waves (Montgomery and Kallenbach, 1997; Montgomery and Enagonio, 1998), or a combined interaction between several large scale influences (e.g. Briegel and Frank, 1997). Yet, all storms which subsequently intensify into mature tropical cyclones eventually sport the characteristic hurricane 'eye': a central region characterized by relatively calm winds, diminished precipitation, and subsiding air. Indeed, viewed from space, the eye is one of the most distinctive features of the mature hurricane, appearing as a broad cloud-free funnel whose lower portions contain clouds more often than not, sometimes whipped into fantastic patterns by mesovortices. Figure 1 shows such a scene, captured by a U-2 flyover of Supertyphoon Ida. The edges of the funnel often slope outward with height, and are defined by a towering, swirling wall of clouds of generally rising air. At the top of the storm, most of the air turns outward, flowing away from the center in a thick cirrus canopy sometimes punctuated by the vigorous updrafts from beneath. Some of the exhaust air turns inward over the eye and sinks. Figure 2 shows the extremely tight eye funnel shape exhibited by Hurricane Wilma (2005), as viewed from space. The success of the Dvorak technique in estimating tropical cyclone intensity[1] points to the fact that storm structure and intensity are inextricably linked.

Tropical cyclones which form eyes are often observed to rapidly intensify with a concomitant increase in structural organization. During eye formation, convection begins to concentrate into an annular ring at some preferred radial distance from the storm center while a region of subsiding air develops over the center. Latent heat released by eyewall convection and adiabatic warming due to central subsidence both contribute to the storm's warm core structure, causing surface pressure falls near the center. Outside the core, surface pressure gradients increase as a result, strengthening the low level radial inflow, leading to increased convergence of moisture and angular momentum, invigorated convection, and an overall intensification of the storm. The dynamical and kinematic response of the vortex to warming of its central column engenders even stronger subsidence and increased eyewall latent heat release: a synergistic positive feedback process. Thus, the importance of the eye/eyewall structure in maintaining and intensifying the storm to a mature state is readily seen. This explains why the eye feature is common to all intense convective cyclones – without an eye, these systems would not be able to reach such a high intensity.

While the intensification role of the eye/eyewall struc-

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[1] The Dvorak Technique estimates a storm's intensity based solely on its appearance (and trend) in visual or infrared satellite imagery, subject to interpretive rules.

ture is well appreciated in the literature, relatively few studies have examined the fundamental causes of the transition from a single-cell vortex – in which the secondary radial circulation extends inward to the central axis – to a two-cell vortex, in which the eyewall separates the outer radial circulation from an inner radial circulation of the opposite sense. Several studies have sought the dynamical causes of the central subsidence, which are indeed a natural and key piece of the eye formation puzzle. Yet, because such subsidence is also a forced response to intensification of the vortex, it may be counterproductive to label it as a causative factor in isolation, just as it would be naive to try to explain eye formation by appealing to any of the reinforcing structural characteristics and intensification dynamics of the mature eye. A complete understanding of eye formation must delineate cause from effect, which may be a difficult task given the strongly coupled nature of intensity and structure.

This extended abstract outlines a research strategy and philosophy for a comprehensive investigation of tropical cyclone eye formation. Historical theories of eye formation are briefly reviewed in the next section. A methodology of investigation is developed, followed by a survey of potential questions under consideration. The final section discusses the broader significance of this research.

# 2. Literature Survey

Formation of the hurricane eye apparently occurs due to the juxtaposition of two structural trends in the developing storm vortex: convection begins to concentrate at some preferred radial distance from the storm center while a region of subsiding air develops within the emerging convective annulus. Various mechanisms have been proffered to explain why and how these structural changes occur, but it is apparent from the literature that the exact mechanism is either unknown or controversial.[2] These may be grossly classified into several categories: (1) kinematic or thermodynamic aspects of the intensifying vortex which act to force subsidence in the center, (2) boundary layer frictional processes and/or geometric considerations which lead to a preferred radius of upward motion and convective forcing, (3) changes which occur in the storm's convective morphology, such as an encircling rain band, which act to focus central subsidence, and (4) distributions of vorticity which act as transport barriers, isolating central air from its surroundings. Eye formation may result as a combination of some or all of these factors. This section provides a brief census of extant theories for eye formation.

[2]For a summary of the state of the problem a couple decades ago, see Anthes (1982); for a more contemporary, nontechnical assessment, see http://www.aoml.noaa.gov/hrd/tcfaq/A11.html.

### *a. Observations and early studies of hurricanes*

While there have not been any observational studies focused on the phenomenon of eye formation, a number of papers provide relevant background to this topic and will be mentioned briefly. An early study (Haurwitz, 1935) showed that the warm core structure of the storm must extend very high in the atmosphere (to the troposphere) and ascertained the basic shape of the eye. Palmén (1948) expanded on this understanding, establishing that the high temperatures in the eye result from the tendency of the vortex to establish a combined hydrostatic and geostrophic-cyclostrophic balance. Although not applied to hurricanes at first, Eliassen's balanced vortex theory (Eliassen, 1952) proved foundational for later studies (discussed below) which examined the slowly changing secondary circulation forced by point sources (convective rings in the axisymmetric framework) of momentum and heating. Jordan (1961) used observations from aircraft reconnaissance to establish that central subsidence rates are more closely tied to the intensification rate than intensity. Landmark studies of hurricane structure and energetics were accomplished in the 1970's (Shea and Gray, 1973; Gray and Shea, 1973; Frank, 1977a,b), while studies of the structural variability of typhoons (including statistics on eye variability) were published about a decade later (Weatherford and Gray, 1988a,b). More recent observational papers have examined the thermodynamics of the eye (Willoughby, 1998), stable isotopes of rain and water vapor (Gedzelman et al., 2003), and ozone concentrations (Carsey and Willoughby, 2005) to determine the source regions of eye air.

### *b. Analytic models*

Some have appealed to two-fluid models for simple explanations of eye formation, but such models are simplistic because the real tropical atmosphere is continuously stratified. Any successful theory must describe the source of the eyewall discontinuity. Nevertheless, such models may provide a glimpse of the relevant physics of the problem. Pearce (1998) presents a two-layer theory and then extends it to a compressible fluid in Pearce (2004). Gravity waves, vortex tilting, and production of azimuthal vorticity have been cited by some as important factors for eye formation (see Pearce 2005), but the interpretation of these are still under debate (see Smith 2005). Clearly, there is still some confusion on this topic in the literature. Finally, the role of buoyancy (and its definition) in vortex intensification has recently been considered by Smith et al. (2005).

### c. *Forced subsidence theories*

Many theories have been put forth to explain the physical or dynamical reasons for central axial subsidence in the cyclone core. As mentioned previously, such subsidence is clearly involved in the maintenance of the eye, however its role in eye formation is unclear. These subsidence theories can be grouped into two categories: kinematically-forced or dynamically-forced. In the first kinematically-forced theory, Malkus (1958; cf. Malkus and Riehl, 1960) hypothesized that eye air mixes with high angular momentum eyewall air, causing air to be centrifuged out of the eye at low levels. Subsidence then occurs to maintain mass balance. Kuo (1959) elaborated further on her idea and also considered integral constraints, defining a Bernoulli equation along a streamline of the inflowing air. Considering that the total energy of inflowing air is limited, yet the angular momentum continues to increase as air approaches the center, he showed that there exists a limiting radius beyond which the converging current cannot pass. This air is then forced upward.[3] Kuo used this theory to make calculations of eye radius with and without surface friction and came up with reasonable eye sizes. The effect of surface friction is to deplete the angular momentum of the inflowing air, allowing further radial penetration and hence, smaller eyes. Carrier et al. (1971) also construct a model of the mature hurricane which considers the role of the frictionally-driven recirculation of the eye in maintaining the intense storm. Willoughby (1995) points out these theories require supergradient flow in the eye in order to maintain central subsidence; since observational evidence for this is lacking, he concludes that these theories must be incorrect.

Smith (1980) proposes a dynamical explanation, suggesting that central subsidence can be accounted for in the balanced equations of motion due to the outward spreading of radial pressure gradient with height at the levels at which the winds are approximately in gradient wind balance. This downward axial pressure gradient force almost exactly opposes the vortex-scale upward buoyancy force of the warm eye air. Another theory involves symmetric heating of the vortex: Willoughby (1979b) and Shapiro and Willoughby (1982) posit that central subsidence is forced by the latent heat released in convective rings. These investigators conducted a scaling analysis of Eliassen's balanced vortex model (Eliassen, 1952) to show that secondary circulation leads to a slow evolution of the axisymmetric vortex. In weak systems (tangential winds of less than 35 m $s^{-1}$), the restraining influences of structure and boundaries lengthen vortex evolution time scales, but for higher wind speeds, these influences diminish in importance resulting in faster evolution. For maximum winds speeds greater than 35 m $s^{-1}$, they report "recirculation of air within the vortex core tends to form an eye." This theory also offers a nice dynamical description of convective ring contraction, explaining a portion of the concentric eye phenomenon.

### d. *Theories involving the storm convective morphology and/or heating asymmetries*

Another class of theories invokes convective asymmetries as a mechanism for eye formation. The first is the "encircling rainband theory" put forth by Willoughby (1979a, 1990a, 1995). Like their parent hurricanes, spiral rainbands also exhibit an in-up-and-out radial circulation, with upward motion in the vicinity of the rainband, and subsiding motion in the near-environment. Due to the curved geometry of spiral bands, subsidence is favored and concentrated on the inside of the band. Thus, a spiral band encircling the center of a developing system will favor central subsidence. Conversely, if an outer spiral band encircles an already formed eye, the effect may be to force subsidence over that eye, weakening it (Samsury and Zipser, 1995). Other convective asymmetries may also help or inhibit eye formation. Simpson et al. (1998) report that hot towers were present in the nascent eyewall structures of some developing storms and that these features contributed substantially to the development of the warm core. Simpson et al. (1997) and Reasor et al. (2005) advance the view that the latter stages of tropical cyclone formation are a stochastic process, whereby interacting mesoscale circulations interact to build up the vortex-scale circulation. Relating this view to the present problem, eye formation may likewise be thought of as a stochastic process, depending sensitively on the evolution and ecology of the convective morphology.

Intense extratropical cyclones and hybrid systems sometimes sport a warm region at their center (as observed on infrared satellite imagery). It is not always clear whether these structures are bona fide eyes, but an occlusion process may be involved in such cases. It is not clear how relevant this mechanism would be for tropical cyclone eye formation, however other effects of horizontal asymmetries may be important in several regards. Pfeffer and Challa (1992) showed that environmental asymmetries play a crucial role in the intensification of storms to hurricane strength (although they did not discuss the formation of eyes) due to the resulting eddy fluxes of angular momentum and heat. They demonstrated that such eddy fluxes were vital for the transformation of an incipient disturbance into a self-sustaining storm, driving a secondary circulation that spins up the circulation and in-

[3]This aspect of Kuo's theory is quite appealing from a parcel perspective, and such ideas have resurfaced in recent years (see Zhang et al. (2005).

creases transport of heat and moisture towards the center. Other studies have examined the effects of heating asymmetries within the vortex. Möller and Shapiro (2005) find that "the structure of the spun-up hurricane vortex, in particular preexisting asymmetric features, can have a substantial influence on the character of the response to an additional diabatic heating asymmetry." Thus, the ultimate vortex evolution and intensification are quite sensitive to the convective morphology – small changes that control convective activity can have a substantial lasting consequence for the intensification of the storm. Other studies (Shapiro, 2000; Wang, 2002a,b) show that the radial distance of the asymmetric heating from the center does not affect the intensification rate of the vortex; this suggests that the heating asymmetries influence structure and intensity through wave activity (convectively-coupled vortex Rossby waves).

### *e. Boundary layer theories*

While the dynamics associated with convective heating and upper vortex structure may be key in forcing central eye subsidence, the tendency for convection to organize into an annulus must still be adequately explained. The frictional boundary layer beneath the storm may provide such a preferential ring of upward mass forcing. Eliassen (1971) examined the boundary layer of a circular vortex and found that the distribution of upward motion obtained depends critically on the boundary condition – a turbulent Ekman layer (appropriate to real vortices) produces a maximum of upward motion out at some radial distance from the center. In contrast, laminar Ekman layers provide a more or less radially-constant upward mass flux near the vortex center. This work was expanded by Eliassen and Lystad (1977), who computed spindown rates in relation to the Rossby number and the drag coefficient. The spindown rate is important to a hurricane (and the question of eye formation), because any intensification mechanisms must overcome the spindown tendency of the boundary layer. Several other papers examine aspects of the boundary layer's contribution to structure or intensity change and are mentioned for completeness (Charney and Eliassen, 1964; Ogura, 1964; Smith, 1968; Yamasaki, 1977; Shapiro, 1983; Montgomery et al., 2001; Smith, 2003; Ingel, 2005; Nolan, 2005a).

### *f. Vorticity-distribution theories*

Vortices involve the dynamical processes of transport and mixing. The polar stratospheric vortex is observed to form an ozone "hole" during polar night because of a transport barrier at the vortex edge. This barrier prevents mixing across the vortex boundary, isolating the low ozone air inside from higher ozone air outside the vortex. Mizuta and Yoden (2001) examine such transport barriers for an idealized stratospheric polar vortex, finding that one type of transport barrier is related to steep gradients of potential vorticity. It has been suggested that the rapidly rotating eye of a hurricane may likewise act as a containment vessel (Willoughby, 1998; Cram et al., 2004). Thus, it may be possible to interpret eye formation as the manifestation of a physical barrier to mixing at the eyewall edge. Several recent papers (Shuckburgh and Haynes, 2003; Nakamura, 2004) give some methods which may be helpful for diagnosing such transport and mixing processes.

Schubert and Hack (1982) examine the role of inertial stability in tropical cyclone formation. They view eye formation as a process which tends to stabilize the vortex since it removes the thermal forcing from the highly stable inner region. There has been some debate as to the nature of the tangential wind profile within the vortex core (gradient vs. supergradient winds; see Willoughby, 1990a; Gray, 1991). Emanuel (1997) notes that horizontal radial momentum diffusion is essential to form realistic eye in tropical cyclones, and other studies have shown that eyewall mixing processes can produce rapid variations in the inner wind profile (Kossin and Eastin, 2001). Thus, mixing and momentum diffusion likely hold an important key to understanding the role of the vorticity distribution during eye formation.

### *g. Laboratory experiments*

While there are very few, if any, laboratory analogs to the problem of hurricane eye formation,[4] physical analogs have been constructed for the somewhat simpler geostrophic vortices of dust devils and tornadoes. In dust devils, there is no latent heating and buoyant energy is supplied from the near-boundary air. Latent heat release can occur in tornadoes, and the vortex dynamics of tornadoes tend to be strongly influenced by the parent storm. Various studies (Davies-Jones, 1973; Church et al., 1979; Walko, 1988) have reported that the nondimensional swirl parameter controls the structure of dust devil- and tornado-like laboratory vortices. A complete literature survey will be required to investigate the bearing of swirl ratio and other vortex parameters to the present problem.

### *h. Modeling studies*

Many modeling studies have simulated realistic eye structures, even studies using very simple model frameworks (e.g. Ooyama, 1969). Perhaps the relative ease of model-

[4] The closest experimental analog to the hurricane is the "upside-down" hurricane vortex simulator of Montgomery et al. (2002). This setup simulates an eye/eyewall structure in order to study eyewall mesovortices.

ing the primary eye structure explains why so few studies have focused on its formation mechanisms – modelers tend to focus on phenomena which are challenging to model.[5] Kurihara and Bender (1982) is an early study which did focus on the the structure and maintenance of the eye and eyewall.

Gray (1998a) studied the eyes formed in numerically-simulated hurricanes and polar lows. She found eye size to be relatively insensitive to initial relative and planetary vorticity for rapidly rotating eyes. This was not true of eye simulations in polar lows, which tended to produce weakly-rotating eyes. Polar low eye size was found to be related to the rate of subsidence in the core, with increased subsidence producing larger eyes.

Zhang et al. (2005) successfully modeled the record 370 km diameter secondary eyewall of Typhoon Winnie (1997) using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5). Somewhat reminiscent of Kuo's (1959) theory, they suggest eye size is constrained by the distribution of environmental angular momentum and the maximum kinetic energy that is achieved by the inflowing air. Larger wind circulations *favor* a larger radius of maximum winds (and hence, a larger eye), but do not uniquely determine eye size. They point to the importance of kinetic energy production, frictional loss of angular momentum of inflow, and other factors such as static stability and vertical mixing of momentum.

Finally, there are numerous other tropical cyclone modeling papers which did not specifically focus on eye formation, but whose methods may provide useful guidance to this work. Such studies include Braun (2002) and Krishnamurti et al. (2005). Some other recent theoretical and/or numerical modeling studies on dust devils and tornadoes may also prove useful (Finley, 1997; Nolan and Farrell, 1999a,b; Nolan, 2005b; Kurgansky, 2005).

# 3. Methodology

In atmospheric science, progress often involves a trifold approach, consisting of observations, theory, and modeling. New and more complete observations of various phenomena often provide the impetus to advance new theories or kill unsuccessful ones, while numerical modeling offers a virtual laboratory for testing and refining those theories. This general philosophy is being followed in developing the methodological approach for this research.

[5]This may explain why so much attention has instead gone to the problem of secondary eye formation – until recently, few if any simulations have been able to simulate concentric eye phenomena starting from the genesis stage.

*a. Observational approach*

One of the longstanding challenges of studying hurricanes is that they spend most of their time over the data-sparse oceans. Observations from an occasional ship, buoy, or island can provide surface data, but these data are nowhere near the spatial resolutions necessary to characterize the evolution of the surface wind field. Geostationary satellite platforms provide a detailed top-view of the storm cloud structure, but the initial stages of eye formation are nearly always obscured from satellite view by a central dense overcast. *In situ* observations from aircraft reconnaissance have done much to advance the understanding of hurricane dynamics and energetics, however many of the coordinated multiple aircraft campaigns have focused on intense storms that already possessed well defined eyes (e.g. Hawkins and Rubsam, 1968; Hawkins and Imbembo, 1976). In addition, logistics of aircraft reconnaissance (e.g. crew rest requirements, limited fuel capacity, and a small number of aircraft) generally prohibit continuous research missions longer than about eight hours, while the period of interest for eye formation may be closer to 12 to 24 hours in duration.[6]

Despite the shortcomings of the traditional observing platforms, the recent implementation of several new remote sensing platforms should prove invaluable in quantifying the intensity and structural characteristics during eye formation. The first class of these new platforms include the satellite-based passive microwave radiometers, which measure terrestrial microwave radiation upwelling through a storm's clouds and moisture. Passive microwave sensors were flown on satellites over tropical cyclones as early as 1972 (Allison et al., 1974) and have flown operationally since 1978, but the higher resolution instruments and refined algorithms of the Advanced Microwave Sounding Unit (AMSU) now allow retrieval of the storm's thermal structure as well as several geophysical parameters including cloud liquid water, total precipitable water, and rain rate (Kidder et al., 2000). Since a storm's upper level warm anomaly is directly related to its intensity through minimum surface pressure (through hydrostatic balance) and tangential wind structure (through gradient wind balance), microwave sounders have allowed the development of algorithms to estimate intensity (and size) independently of the Dvorak technique (Demuth et al., 2004), providing a unique perspective on the relationship between structure and intensity.

Another key advantage of multispectral microwave instruments is that they can distinguish between intense convection and warm rain precipitation. In the 85 GHz

[6]Theoretical work by Carrier (1971) suggests that the *e*-folding time for eye formation itself can occur on a much shorter time scale. This is borne out by observations of rapidly developing eyes.

channel, scattering from precipitation-sized ice particles lowers equivalent blackbody brightness temperatures, demarcating regions of intense convection (Hawkins et al., 2001). Thus, by comparing images from several channels, one can determine the convective morphology (i.e. the location and configuration of eyewall and rainband convection) of the storm at a given instant in time (Karyampudi et al., 1999). Since multispectral microwave instruments are now flying on a constellation of satellites, such observations have become much more frequent over the past few years, partially offsetting the drawback of low temporal resolution that previously hampered this observation platform.

In 1997, the Tropical Rainfall Measurement Mission (TRMM) satellite was launched, adding another remarkable remote sensing platform to the mix. Besides radiometers for the visible, infrared, and microwave spectral bands, TRMM carries the first space-based precipitation radar. One key advantage of an active space-based radar is that it can provide a three-dimensional view of the precipitation field (Kummerow et al., 1998). TRMM also carries a Lightning Imaging System (LIS). A recent study (Kodama and Yamada, 2005) used the unique combination of TRMM's instrument package to determine the detectability and configuration of tropical cyclone eyes over the Western North Pacific. Their study stratified detectability against intensity and life cycle stage and also examined eye size.

Another diverse class of instruments is now providing quantitative descriptions of the surface wind field under and around tropical cyclones. Space-based scatterometers, such as *QuikSCAT* (launched in 1999) and *WindSat* (launched in 2003), quantify the outer core strength of tropical cyclones using algorithms to retrieve wind magnitude and strength based on scattering from surface capillary waves (for a description of the *QuikSCAT* payload and mission, see Lungu, 2001). Since 1998, operational reconnaissance aircraft have been using the newer, more accurate National Center for Atmospheric Research (NCAR) Global Positioning System (GPS) dropwindsondes instead of less accurate Omega dropwindsondes (Hock and Franklin, 1999). The GPS dropwindsondes have provided an unprecedented view of the kinematic and thermodynamic structure of eyewalls and have caused a revision of operational flight level-surface wind reduction factors (Franklin et al., 2003). Another instrument, the airborne Stepped Frequency Microwave Radiometer (SFMR), has matured and can now provide high resolution observations of the surface wind field, even in the extreme wind regime. Since the GPS dropwindsondes sometimes report at altitudes of less than 10 m, they provide invaluable "ground truth" data for the ongoing SFMR calibration.[7]

The observational component of this work aims to determine the intensity and structural characteristics of intensifying storms during the period leading up to and during eye formation. Given the historic dearth of intensely-observed cases of eye formation,[8] it is expected that most relevant case studies will have to be constructed in a hybrid fashion by utilizing the diverse multiplatform remote sensing instruments (AMSU and other advanced microwave radiometers, TRMM, *QuikSCAT* and *WindSat*) in conjunction with Geostationary Earth Orbit Satellites (GOES) radiometric data, and augmented by aircraft data (flight level wind data: wind, thermodynamic, and microphysical data; air-based radar; GPS dropwindsondes; and SFMR data, when available) and/or ground radars (if eye formation occurred close to the coast).

Much of the microwave and reference GOES imagery has been archived since 1997 on the Naval Research Lab's Tropical Cyclone web page.[9] Also, CSU's Atmospheric Science Department and the Cooperative Institute for Research in the Atmosphere (CIRA) possess unique strengths in the remote sensing arena, so the author plans to seek access to CIRA's GOES IR tropical cyclone archive[10] and microwave imagery archive and associated AMSU products. Collaboration with the Hurricane Research Division (HRD) is planned in order to access research grade data from aircraft.

Finally, global model operational analyses (or reanalyses) offer a 'synthetic' view of the near-storm observational data.[11] Thus, it may be valid to use such analysis or reanalysis data to determine environmental factors which affected the storms of interest during eye formation. Several institutions, including CSU-CIRA, NCAR, NCEP,[12] and HRD, are teaming to devise better data assimilation methods appropriate for the core of hurricanes, with the

[7] The SFMR is currently only installed on the National Oceanic and Atmospheric Administration (NOAA) P3 research aircraft, so the number of cases of eye formation with SFMR data may be quite small.

[8] Simpson et al. (1998) note that prior to the early 1990's, one has to go back to Daisy (1958) to find an Atlantic storm that was intensively studied during the formative phase. In 2005, several field experiments were conducted in the Atlantic and Eastern Pacific basins: the Hurricane Rainband and Intensity Experiment (RAINEX) and the Intensity Forecasting EXperiment (IFEX). Since many storms formed and intensified relatively close to the continental United States that year, the author expects that these field experiments will yield several good cases of eye formation.

[9] Available online at http://www.nrlmry.navy.mil/tc_pages/tc_home.html.

[10] The GOES IR archive consists of storm-centered infrared imagery from Atlantic tropical cyclones from 1995 to the present. This data will provide a temporal reference of the cloud-top evolution during eye formation.

[11] In recent years, the NOAA Gulfstream IV jet has been used to sample the near-storm environment around threatening Atlantic storms. This has provided a rich new data source to constrain the global analyses.

[12] National Centers for Environmental Prediction

goal of providing high resolution data to initialize the operational hurricane models. It is possible that this ongoing effort may yield a method for constructing a detailed mesoscale model-based reanalysis of past storms, which would be of great interest to this work.

Through observational study, this works seeks to:

- Formulate a useful definition for detecting when an eye has formed.
- Determine the intensity/size characteristics of the initial eye at the time it is first detected and when it reaches a mature state.
- Trace the evolution of the complete wind profile during eye formation.
- Determine the observable internal and external factors which control initial eye size.
- Characterize the convective morphology (rainbands, convective arcs, convective rings, isolated cells) and ecology during eye formation using microwave imagery and space-, land-, and aircraft-based radar.
- Determine the role of the environment during eye formation by examining the thermodynamic and angular momentum distribution at the inflow source radius.
- Diagnose cases of "failed eyes" in nondeveloping systems and contrast these to "successful eye" cases in developing systems.

### *b. Modeling approach*

The modeling component of this research will involve idealized and full physics numerical simulations of eye formation using the Weather Research and Forecasting (WRF) Model, a next generation multipurpose model suitable for regional, mesoscale, and microscale simulations. WRF actually consists of two dynamical cores, and from that regard, can be considered as two different models – but the physical and microphysical parameterizations are being standardized for use in both cores, so many different "flavors" of WRF are possible. The Advanced Research WRF (ARW) Model (developed mostly at NCAR) has been focused on research applications, and features a dynamical core with an Eulerian mass solver (for a description of the ARW and its numerics, see Klemp et al., 2000; Wicker and Skamarock, 2002; and Skamarock et al., 2005). The Nonhydrostatic Mesoscale Model (NMM) version has been developed mostly by NCEP with a focus on operational use. It uses a hybrid pressure-sigma vertical coordinate; the numerics are split into hydrostatic and nonhydrostatic portions (for details on the NMM numerics, see Janjic et al., 2001; Janjic, 2004). The Hurricane WRF model (HWRF) is currently being developed based on the NMM core, and is slated to replace the current operational Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model in 2007. Since these are relatively new models, it will important to first find the optimal model configurations for tropical cyclone simulations (e.g. domain size, lateral boundary conditions, underlying boundary conditions, physics options, nesting configuration and gridpoint spacing). This process may involve some trial and error, but the literature should offer some guidance on some of these issues (e.g. Rosenthal, 1971; Braun and Tao, 2000).

Two challenges of the idealized experiments are to determine the best method of initializing the model and to find the most dynamically-relevant manner of representing the convective physics (e.g. parameterized latent heating vs. moist and explicit convection). A battery of idealized experiments is planned to test the "eye-a-genicity" of various convective morphologies, such as curved bands with embedded hot towers. A proper initialization should incorporate the desired configuration of convective elements into the vortex in a balanced manner, so as not to adversely affect the forward model integration. Smith (2006) gives a simple method to calculate the balanced density field for an axisymmetric vortex in a compressible atmosphere – this method may be quite applicable to this work. For asymmetric initializations, a nonlinear multigrid solver such as MUDPACK may be useful. The expression of the morphology may also be key: some researchers (Nolan, 2004) point out that while numerous studies have shown that *wind* asymmetries always lead to intensification of the symmetric vortex (through the axisymmetrization process described in Montgomery and Enagonio, 1998), *heating* asymmetries sometimes fail to produce intensification and can even lead to weakening.

Another set of idealized experiments will investigate the relationship between eye formation and initial vortex intensity and size. The goal of these experiments will be to determine the intensity threshold(s) at which the model eyes form. The model will be initialized with a weak tropical storm-strength system that has already undergone genesis (or is undergoing genesis, if it proves difficult to obtain a realistic weak storm from idealized conditions). The relevant parameter space involving the initial vortex structure (i.e. intensity, wind profile shape, and swirl ratio), physics (precipitation loading and cloud microphysics effects), convection (distribution and mass fluxes of updrafts and downdrafts), and surface properties (transfer coefficients for drag and heat) can be varied across the experiment to elucidate the critical thresholds of eye formation.

Finally, this work will examine simulations of eye formation in real storms. The mode of genesis may play an important role in eye formation, so this hypothesis should be examined and compared with the observational evidence. Cases of failed eyes should be identified to determine what mechanisms (if any) prevent the successful formation of an eye. It will be of interest to test WRF's ability to model small-eye storms. Storms with extremely small eyes (diameters of less than 10 km) challenge even current operational models, since the eye is only partially resolved even on the finest nested mesh. A series of experiments is planned to simulate the record small eye (2 n mi in diameter!) observed in Hurricane Wilma on 19 October 2005 (Knabb et al., 2005). The role of model resolution in simulating storm intensification and structure will be examined.

Designing an experiment, initializing it, running the model, and then actually getting a useful result are only a part of the modeling task. The remaining challenge involves extensive post-processing and analysis to learn why the system behaved in the way it did and what this says about the relevant physical and dynamical mechanisms at work. This work plans a variety of model diagnostics, some of which include the following:

- To determine useful measures of the model vortex's intensity, aspect ratio, swirl parameter, inflow angle, and inflow source radius.

- To examine the evolution of the momentum, $\theta_E$, and potential vorticity (PV) fields during eye formation.

- To diagnose the strength of the induced axial subsidence and determine the contributive mechanisms (i.e. by comparing the subsidence predicted from balanced dynamical theory to the subsidence observed in the model).

- To compute Lagrangian parcel back-trajectories from the eyewall and eye during eye formation. This should help determine the source characteristics for these two types of air and shed light on the mass recycling rates in the incipient eye (following Cram et al., 2006). Budgets of angular momentum, thermodynamic energy, moisture, kinetic energy, and PV of the eye and eyewall air can then be computed along the parcel trajectories.

- To test the sensitivity of eye formation to surface fluxes. These fluxes could be held fixed, or allowed to vary through a coupling of the air-sea interface.

*c. Theoretical approach*

There seems to be a general surplus of theories on eye formation, yet few of these have been rigorously tested. One of the goals of the modeling component of this work will be to determine the validity of historic and current theories. This researcher may attempt to modify these theories to correct shortcomings (if possible), but feels that it would be premature to attempt a new analytic approach to this problem before rigorously surveying and testing current theories. Thus, an attempt at a holistic analytic approach to this problem will likely occur during the latter stages of this research.

# 4. Some Questions for Consideration

The following questions have been formulated to define potential avenues of inquiry for this work.

- What is the most useful way to define the eye? Are there different types or classes of eyes (i.e. rapidly rotating vs. weakly rotating)?

- What are salient mechanisms and dynamics that drive a single-cell vortex structure to a two-cell vortex structure?

- What role does central subsidence play in eye formation? What forces the subsidence? Can subsidence trigger eye formation?

- Convection must obviously play an important role in eye formation, but what role? What role does the convective strength play? The distribution and concentration of convective elements and their radial distance from the storm center? Their morphology and geometrical arrangement into rings, spiral bands, or clusters?

- It is also believed that friction plays a critical role in eye formation. What is that role? As the storm intensifies, are feedbacks between the sea state and the resulting frictional drag exerted on the atmosphere important for eye formation? What are the microphysical effects of increasing sea spray on the storm's cloud and precipitation microphysics?

- What role does intensification play during eye formation? Is eye formation an instability process triggered at an intensity threshold? If so, what is the nature of the trigger and the actual intensity threshold for eye formation? What is the least intense tropical cyclone to sport a bona fide eye? What is the most intense storm to not possess a clearly defined eye?

- Is eye formation a bifurcation phenomenon, with multiple states of equilibria? If so, what mechanisms are responsible for pushing a storm back and forth between equilibria states? Can a phase space diagram be constructed for eye formation? What are the relevant parameters of this phase space?

- Are there multiple dynamical pathways to eye formation, or do all intensification routes lead to one common eye formation pathway, perhaps dictated purely by geometry and friction?

- If there are multiple modes of eye formation, which one is optimal for the greatest intensification rate? How much of the storm's actual realized maximum intensity depends on the storm's initial structure and the route it followed to get there?

- What are the relationships between overall storm size and initial eye size? Eye size and intensification rate? Eye size and a storm's ultimate realized intensity? What role does the environment play in these relationships?

- How much of constraint does initial structure place on the *final* mature structure?

- What role do asymmetries play in eye formation? At what threshold do asymmetric mixing processes become important as the storm strengthens?

- What is the exact role of gravity waves during eye formation? Of vortex Rossby waves?

- What determines the eye shape and eyewall slope in real storms? How is eye shape affected by intensity or rate of intensification? Movement? Shear?

- Why do some storms rapidly intensify as they form eyes, yet others do not? Are there commonalities in the developing eyes of storms which subsequently undergo rapid intensification in the hurricane stage?

- What role does eye and eyewall buoyancy play during eye formation?

While it is doubtful that this work will answer *all* of the above questions satisfactorily, the researcher hopes that useful answers will be found for many of them. The main expected result of this research is to obtain in hand a comprehensive observational, numerical, and theoretical description of eye formation applicable to a stratified and rotating cloudy vortex. It is also expected that this work will elucidate the complex relationship between eye formation and the intensification of the vortex. Finally, the author hopes that this work will advance a new dynamical systems perspective for the eye formation problem.

# 5. Broader Significance

Besides occurring in intense tropical cyclones, eyes or eye-like phenomena have been noted across a broad spectrum of geostrophic vortices: tornadoes and dust devils (Bluestein et al., 2004a,b; Sinclair, 1973), polar lows, intense extratropical cyclones, and hybrid systems. Vortices having much in common with tropical cyclones have been noted over the Mediterranean (Reale and Atlas, 2001; Emanuel, 2005) and even Lake Huron (Miner et al., 2000). Indeed, past researchers have proposed that *some* polar lows are actually Arctic hurricanes (Emanuel 1989). Thus, the results of this work are expected to have at least some bearing on this broader range of eye phenomenon. For instance, if a generalized theory is found to describe the one-cell/two-cell structural transition based solely on swirl parameter and/or boundary layer frictional effects, this result may apply to some or all geostrophic vortex types, irregardless of whether or not the vortex contains moist convection.

The empirical Dvorak technique of intensity estimation (Dvorak, 1975, 1984) has been widely and successfully applied in basins around the world. The underpinning assumption of the standard technique is that the present intensity of a system is related to its convective organization and vigor. Similar objective methods, such as the Objective Dvorak Technique (ODT, Velden et al., 1998) are also based on this assumption, relating intensity to the structural 'scene' (i.e. "spiral banding" or "embedded eye", etc.). When an eye is present, the ODT relates overall storm intensity to the coldness and symmetry of the convective ring surrounding the eye and the eye temperature (a colder, more symmetric ring surrounding a warmer eye yields a higher intensity estimate). Such objective measures are proxies for the height to which the convection reaches (inferred from cloud top temperatures) and the definition of the eye and the strength of the associated eye subsidence (inferred the warmness of the eye temperature). Yet the physical processes that cause such a strong relationship are not well understood (Elsberry et al., 1992). The findings of this work should shed light on this enigma and may provide a knowledge base upon which to build better intensity estimation techniques.

Intense tropical cyclones are often observed to undergo secondary eyewall replacement cycles, during which an outer convective ring and associated tangential wind maximum forms and undergoes contraction. As the new, outer eyewall contracts, its convection imposes a new radial circulation on the storm, cutting off moist inflow and forcing subsidence over the inner eye. Thus, the outer eyewall inhibits convection of the inner eyewall and eventually kills it, leaving a relict circulation within the larger new primary eye. This cycle has been well-documented by following the temporal evolution of radial profiles of tangential wind obtained from aircraft (Willoughby et al., 1982; Black and Willoughby, 1992). Although the relevant dynamics of ring contraction are well understood (Shapiro and Willoughby, 1982), the mechanism by which convective rings form is not, although Willoughby (1990b) suggests that the convective ring structure may be a normal mode, or attractor, of the system. Follow up work by Nong and Emanuel (2003) suggests that convective rings undergoing amplification through a Wind-Induced Surface Heat Exchange (WISHE) mechanism if the lower atmosphere is moist enough. Due to cool downdrafts and thermal stability in the outer regions of storms, their modeling results suggest that large scale external forcings are necessary to initiate convective rings. Eddy angular momentum fluxes caused by interactions between the storm and the environment (e.g. an upper trough) could provide such a forcing (see Mollinari and Vollaro, 1990; Molinari et al. 1995), yet concentric eye phenomena are commonly observed in storms that are highly axisymmetric. This fact suggests that internal dynamics play a critical role. Rapid filamentation zones (Rozoff et al., 2006) and the role played by a vortex Rossby wave stagnation radius (Montgomery and Kallenbach, 1997) appeal to the internal dynamics view, since both apply to strongly-rotating vortices. In contrast, primary eye formation occurs in a weak-to-moderate rotation regime. Regardless, both primary and secondary eyewalls may share similarities with respect to air/sea exchange regime under the nascent eyewall, where winds range from 20 - 40 m $s^{-1}$. This work should lead to increased understanding of at least some aspects of secondary eyewall formation.

This work also has important societal implications. The massive disruption and havoc wreaked by the hyperactive 2004/2005 Atlantic hurricane seasons have graphically illustrated that even advanced technological societies can be extremely vulnerable to tropical cyclones. While the past several decades have seen steady improvements in track forecasts (McAdie and Lawrence, 2000), improvements in forecasts of storm intensity and structure have lagged behind (Avila, 1998). Predictions of secondary storm effects such as storm surge and rainfall depend to a large degree on accurate foreknowledge of a storm's intensity and structure. Eye formation strongly impacts both intensity and structure, so an increased understanding of eye formation should have positive implications for intensity prediction.

Ultimately, the details of hurricane intensity and structure prediction are likely to be handled by the new generation of high resolution full physics numerical models. Before HWRF becomes operational, a careful investigation of eye formation should be undertaken to ensure that artificial model sensitivities do not delay eye formation or lead to spurious eyes. While the model is likely to utilize explicitly resolved convection, at least on the inner domain, the impact of model resolution and nesting configuration on eye formation should be determined. This work aims to contribute towards this goal.

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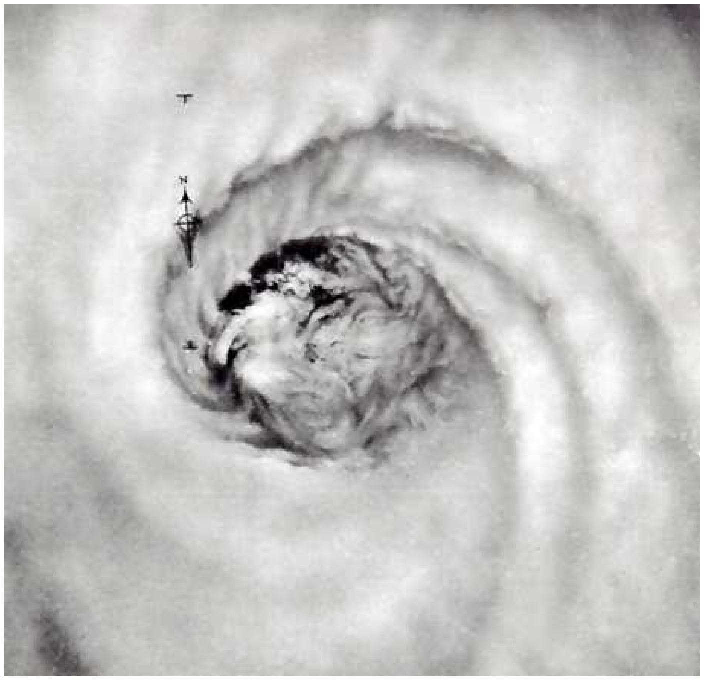

Figure 1: A high altitude aerial photograph of Supertyphoon Ida taken from a U-2 spyplane on 25 September 1958 (c.f. Fletcher, 1961). Photo courtesy of Frank Marks (NOAA/AOML/HRD). [Photo has been digitally enhanced to remove dust specks.]


Figure 2: The tight eye funnel of Hurricane Wilma. Photo taken from the International Space Station at 8:22 AM CDT, 19 October 2005. Wilma was near peak intensity at this time, with a minimum sea level pressure of 882 hPa and maximum sustained surface winds of 160 kt. [NASA Photo ISS012-E-5241].