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LOW-LEVEL THERMODYNAMIC, KINEMATIC, AND REFLECTIVITY FIELDS
OF HURRICANE GUILLERMO (1997) DURING RAPID INTENSIFICATION

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ABSTRACT

The two NOAA WP-3D aircraft simultaneously sampled Hurricane Guillermo (1997) as it underwent rapid intensification (RI). Seventy Global Positioning System dropwindsondes (GPS sondes) with sufficient data for analysis were jettisoned within 300 km of the tropical cyclone (TC) center over two days. Sampling occurred shortly after RI commenced on 02 August with the TC deepening 25 hPa by the time the aircraft returned the following day to a steady-state TC.

The GPS sondes were quality controlled and treated with a cubic spline to produce lower tropospheric (≤ 4 km) kinematic and thermodynamic composites for each day. A quasi-stationary wavenumber-1 reflectivity pattern, with intense convection confined to the east eyewall, existed on both days. Winds increased 15 m s^{-1} within the inner core, but the north-northeast eyewall remained $7\text{-}10 \text{ m s}^{-1}$ greater than the south-southwest eyewall on 03 August. Thus, Guillermo began and concluded RI with an asymmetric reflectivity and kinematic structure. Increased wind speeds were confined primarily to within 100 km of the TC center, with some regions beyond this radius decreasing more than 10 m s^{-1} . Net latent heat release calculated over a 60 km radius from the TC center increased 21% between days. In the lowest kilometer asymmetric inflow on 02 August became axisymmetric on 03 August. On both days the depth of the inflow layer over the northern portions of the TC decreased with decreasing radius from the circulation center. Above 1 km altitude regions of maximum inflow were aligned with regions of maximum outflow across the circulation center and rotated anticyclonically with height.

On 02 August eyewall convection spiraled into an oval shaped eye and reduced the eye diameter, coinciding with substantial surface pressure decreases. A circular, smaller eye was observed on 03 August. It is hypothesized that a subsidence induced capping inversion over the western half of the TC prevented the vertical mixing of the boundary layer and allowed for the build-up of θ_e near the sea surface. This high θ_e air became part of the strong inflow in the southeast quadrant that maintained the deep convection located in the eastern side of the eyewall.

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CHAPTER 1:

INTRODUCTION

1.1 Background

Rapid intensification (RI) is a term reserved for significant deepening of a tropical cyclone (TC) over a short period. Forecasting RI is a challenging task and is critical for TCs threatening coastal populations. Holliday and Thompson (1979) and Kaplan and DeMaria (2003) concluded that the most intense TCs often undergo RI, yet the process of how a TC evolves during RI is not well understood. Rarely are observations obtained during RI that can resolve how the inner core, defined as the eye, eyewall, and rainbands within 75 km of the circulation center, respond to or bring about the rapid deepening. Hurricane Guillermo (1997) underwent RI in early August over the eastern North Pacific Ocean and was the first TC to be sampled with Global Positioning System (GPS) dropwindsondes, referred to hereafter as GPS sondes. The two National Oceanic and Atmospheric Administration (NOAA) WP-3D aircraft sampled the TC over two days as part of the Vortex Motion and Evolution Experiment. Eighty-two GPS sondes were deployed within 300 km of the circulation center of Hurricane Guillermo during and subsequent to a period of RI. This study utilizes the data obtained from GPS sondes to examine the kinematic and thermodynamic structure of the TC from the surface to 4 km. Tail and lower fuselage (LF) radar reflectivity fields from the NOAA aircraft are incorporated into the analysis to determine how the low level inner core evolves in an effort to better understand RI processes.

1.2 Previous Work

There have been a series of RI climatological studies, albeit with varying definitions for the process. Frederick (2003) developed a RI climatology using a database of all North Atlantic major hurricanes from 1851 to 2001. He defined RI as a wind increase of at least 17 m s^{-1} in 24 h. A total of 257 major hurricanes formed during this period and 92 (36%) met the RI criteria. The seasonal variation of RI was also examined. The first half of the season (JJA) accounts for less than 25% of all RI major hurricanes while September alone accounts for more than half.

Kaplan and DeMaria (2003) also examined RI cases in the North Atlantic basin. Their examination period was much shorter (1989-2000) than Frederick (2003), but included all TCs (163). RI was defined as the 95th percentile of over-water 24 h intensity changes. This equated to a 15 m s^{-1} increase over 24 h. Fifty (31%) TCs underwent RI during this period. RI was found to occur in 60% of all hurricanes, and in 83% of major hurricanes. All category 4 and 5 hurricanes underwent RI at least once during their existence. August and September accounted for 72% of the RI cases, while June and July accounted for only 5%.

Holliday and Thompson (1979) used minimum pressure from reconnaissance flights to develop a RI definition for the western North Pacific basin. The period from 1956-1976 provided 305 typhoons with sufficient data to define RI as the 75th percentile of the intensifying typhoons, or a 24 h pressure drop of 42 hPa. Seventy-nine of the 305 typhoons underwent RI. The majority of these typhoons (59 or 75%) had a central pressure less than 920 hPa, and all six minimum central pressures less than 888 hPa were attained as a result of RI. When the duration and rates of development were examined,

peak falls were found to occur during the first 6 h of the RI period. Fifty-six typhoons had sufficient observations to determine the onset of RI within 3 hours. The majority (64%) of these typhoons began RI during the night. Holliday and Thompson (1979) suggest instability caused by diurnal variations in the middle and upper troposphere may be a factor that contributes to RI.

Brand (1973) analyzed 25 years (1945-1969) of western North Pacific data to define RI as a 24 h wind increase of at least 26 m s^{-1} . When organized by month, favored geographic locations for RI were discernable. From August to October preferred locations for RI moved south and east. As in the previous studies, Brand (1973) found September to have the greatest number of typhoons that underwent RI.

DeMaria and Kaplan (1994) developed the Statistical Hurricane Intensity Prediction Scheme (SHIPS) to provide forecasters with real-time intensity forecasts for Atlantic and eastern North Pacific TCs. SHIPS incorporates climatological, persistence, and synoptic predictors to produce an operational intensity forecast. Nine years later, Kaplan and DeMaria (2003) enhanced SHIPS by providing forecasters with a simple technique for estimating the probability of RI. This technique examines the magnitudes of five predictors (previous 12-h intensity change, sea surface temperature (SST), low level relative humidity, vertical shear, and the difference between the current intensity and the maximum potential intensity (MPI)). They divided their database into RI and non-RI cases and then calculated the differences between the two groups for the five RI predictors. A two-sided t test indicated that three of the differences were 99.9% statistically significant: RI cases had less shear (-3.6 m s^{-1}), warmer SSTs (0.9°C), and more 850 – 700 hPa relative humidity (4.3%). All five of the differences were used to

create thresholds to determine whether RI was likely. When all five of the thresholds were satisfied, less than 2% of the total sample, there was only a 41% chance of RI. Clearly, a TC rarely finds itself in an environment where favorable conditions occur simultaneously and also suggests there are additional physical processes that must be examined to explain and understand RI.

Studies of individual TCs elucidate some of the important factors involved with RI. Bosart et al. (2000) examined the RI of Hurricane Opal (1995) where large-scale environmental influences, storm-scale internal dynamics, and air-sea interaction all may have contributed to RI. Opal crossed over a warm core eddy in the Gulf of Mexico which provided an increase in oceanic heat and moisture fluxes, an approaching trough from the northwest provided divergent flow aloft that established a favorable outflow channel, and there are indications that Opal may have undergone an eyewall replacement cycle (ERC) at this time. Before undergoing RI, Opal was far from its MPI and the 850-200 hPa shear was on the order of $2\text{--}3\text{ m s}^{-1}$. Bosart et al. (2000) explains that because of these reasons, intensification was forecast as the TC began to interact with the approaching trough. Upper level divergence preceded eyewall convective growth by nearly 6 h and the onset of RI was attributed to the favorable jet-trough-TC interaction. This interaction is believed to be the primary factor for initiating RI of Opal. Maximum surface winds increased by nearly 15 m s^{-1} shortly before favorable air-sea interaction was able to further intensify the TC as it passed over a warm core eddy. Hong et al. (2000) conducted a modeling study that suggested only 25% (10-15 hPa) of the observed pressure fall during the rapid deepening phase could be explained by the oceanic fluxes from the warm core eddy.

Rodgers et al. (1998) used Special Sensor Microwave/Imagery (SSM/I) satellite instrumentation to derive volume-integrated net latent heat release (LHR) during the RI of Opal (1995). Data within an area defined by the 55 km radius from the circulation center were used in the calculations. Although SSM/I passes were sporadic, observations over the TC were frequent enough to define Opal's large-scale temporal changes of net LHR. Two pronounced spikes of net LHR were observed as Opal traversed across the Gulf of Mexico. The first corresponded with the initiation of rapid pressure decrease and the second occurred simultaneously with the estimated lowest pressure. It was hypothesized that the abundance of net LHR in the middle- and upper-tropospheric region allowed the eyewall to become more buoyant, enhancing the kinetic energy and thereby generating RI.

Franklin et al. (1988) obtained direct observations from the eye of Hurricane Gloria (1985) while it was undergoing RI. Two Omega dropwindsondes (ODWs) were released in the eye less than 5 hours apart as the TC deepened at a rate of 2.5 hPa h^{-1} . During this period the temperature inversion at cloud top significantly strengthened as the 700 hPa temperature rose from 14.0°C to 28.8°C and the relative humidity fell from 100% to 33%. Changes in geopotential heights of pressure levels indicate which layers are associated with the 10 hPa deepening between the two soundings. The 500 mb surface dropped 37 m, showing that the upper troposphere warming accounts for a surface pressure drop of 3.9 hPa. The remaining pressure drop was associated with warming between 500 hPa and the surface. These findings suggest enhanced subsidence in the eye is correlated with RI.

Titley and Elsberry (2000) analyzed the upper troposphere over the outer environment of Super Typhoon Flo (1990) during RI. Azimuthally-averaged 200 hPa radial winds for an annulus 300 km - 1500 km from the circulation center had a relative minimum of outflow during RI, relative to the pre-RI environment. Except for a slight maximum of 8 m s^{-1} outflow near 400-km radius, the average radial winds were about 4 m s^{-1} . The midtropospheric inflow also weakened during the RI. While deep layer (850-200 hPa) shear remained low during RI, shear between 300 hPa and 150 hPa decreased by 35%. The study concluded that the RI appeared to be an internal ($< 300 \text{ km}$) adjustment, perhaps triggered during the pre-RI stage. Titley and Elsberry (2000) noted that a science leader on the aircraft reported concentric eyewalls (CEs) at the TCs center near the end of RI. Presently, research associated with rapid intensity changes has focused on the formation of CEs and ERCs (Kossin et al. 2000, Zhu et al. 2004, Wang 2006).

The occurrence of CEs is a primary mechanism that can cause rapid TC intensity change (Wang 2006). Willoughby et al. (1982) first found CEs to occur for intense, highly symmetric TCs and later stated that they play a major role in the development of many, but not all, major hurricanes (Willoughby 1990). The development of convection and formation of an outer ring are not well understood. As the outer ring reaches a critical distance from the original inner eyewall, however, the more intense inner ring begins to weaken. As the outer ring intensifies, contracts, and replaces the inner eyewall, pressure falls and increased tangential winds ensue. This arrangement of decaying and intensifying rings can be a precursor to RI. There is no evidence to suggest that Hurricane Guillermo (1997) underwent RI due to contraction of CEs.

Previous research associated with Guillermo focused on the role of small concentrated regions of vorticity, or mesovortices. Kossin and Schubert (2001) and Kossin and Eastin (2001) conducted several numerical experiments that suggest thin regions of enhanced eyewall vorticity surrounding a nearly irrotational eye may be a precursor for RI. The annulus of enhanced vorticity breaks down into multiple mesovortices. Extreme pressure falls were associated with the mesovortices and they often contained lower pressure than readings taken near the eye center. This arrangement can result in multiple pressure centers with the possibility of multiple wind centers radially inward of the eyewall. In addition to their ability to decrease minimum pressure, Eastin et al. (2005a,b) argued that mesovortices play a vital role in eye and eyewall mixing processes. High equivalent potential temperature (θ_e) in the low-level eye is mixed with the eyewall and a more buoyant updraft transports high θ_e up the eyewall resulting in a very efficient process for maintaining a robust TC. Zhang et al. (2001) and Braun (2002) have conducted simulations with advection of low-level eye air into the eyewall.

1.3 Goals

Previous climatological investigations conclude that RI is common for high intensity TCs, is more likely to commence at night, and occurs most frequently in September for the Northern Hemisphere. The synoptic environment around a TC does not provide a clear signal when RI is imminent. Passage over warm water with a deep thermocline, enhanced upper level divergence, and CEs are all factors that can contribute to RI.

The Guillermo dataset provides an excellent opportunity to document the changes of a hurricane's inner core as it deepens more than 25 hPa. GPS sonde data will be used to create lower tropospheric (10 m – 4000 m) composite thermodynamic and kinematic fields during and subsequent to RI. Nearly identical flight patterns are flown a day apart and allow for direct comparison between days.

It is hypothesized that the intensification is caused by processes within or near the inner core. A smaller eye diameter, taller eyewall echo tops, and more uniform, heavy rain rates are expected as a result of RI. More symmetric kinematic fields will develop. The increased winds will be confined to the inner core of the TC and the outer core will be minimally impacted. An increase of net latent heat release will result in a deeper more symmetric inflow. Downdrafts that diminish the energy content of the inflow will decrease within the inner core during RI and allow for a more isothermal inflow layer. A more intense, organized TC will produce a radially and axially symmetric temperature structure. Large increases of θ_e under and near the eyewall will play a major role in the RI. Difference fields will be created by subtracting key 02 August composite fields from 03 August composite fields for several atmospheric variables to examine these claims. Composite fields and GPS sonde data on 02 August will be examined further to determine if any clues are provided to possible RI processes. This analysis will contribute to a better understanding of the eyewall interaction with the immediate environment during RI.

CHAPTER 2:

DATA AND ANALYSIS METHODS

2.1 Hurricane Guillermo

Convective clouds moving at typical easterly wave speeds were tracked by satellite across the Atlantic Ocean and Caribbean Sea and entered the eastern North Pacific basin on 28 July 1997. The disturbance gradually became better organized with increased convection as it moved westward, developing into a tropical depression on 30 July. Tropical Storm Guillermo was named 18 hours later and eventually became a hurricane at 1800 UTC 01 August. Shortly after 0600 UTC 02 August, Guillermo began a period of RI that lasted nearly 24 hours (Fig. 1). Data from the “Best Track” shows a 31 m s^{-1} increase and a 54 hPa decrease over 24 hours (1200 UTC 02 August - 1200 UTC 03 August). Slow intensification continued after RI and the TC reached a maximum intensity of 919 hPa on 05 August at 0000 UTC with wind speeds exceeding 72 m s^{-1} (Lawrence 1999).

Guillermo was located over 28-29 °C water that exhibited weak horizontal gradients. A ridge located northeast of the hurricane steered the system westward across the Pacific and 200–850 hPa shear calculated over a radius 200-800 km from the TC center never exceeded 8.5 m s^{-1} . Table 1 details the evolution of the large scale environmental conditions, as well as the intensity and motion of the TC. There was little variability in synoptic conditions that would suggest RI was imminent. SST and shear remained largely constant from 0000 UTC 02 August to 1200 UTC 03 August, when mean sea-level pressure decreased 58 hPa. Figure 2 displays a portion of Guillermo’s track when RI occurred.

2.2 Sampling

On 02 and 03 August, the two NOAA WP-3D aircraft simultaneously sampled Hurricane Guillermo. Sampling occurred shortly after RI commenced on 02 August when the estimated deepening rate was 2 hPa h^{-1} . When the aircraft returned the following day, the TC had deepened at least 25 hPa from the previous mission and was nearly steady-state. Aircraft flew along constant pressure surfaces of 500 hPa and 700 hPa within 300 km of the TC center. Each plane flew the same flight pattern both days such that the lower aircraft visited the center 10 times each day, while the higher aircraft visited the center 6 times over a roughly six hour period (18:30 – 01:00 UTC). This configuration allowed for frequent monitoring of the precipitation fields of the eyewall with the LF and tail radars.

The NOAA WP-3D aircraft are the most advanced and comprehensive of all meteorological aircraft currently in use (Aberson et al. 2006). Two digital research radars are located on the aircraft. The LF radar operates at a wavelength of 5.5 cm (C-band) and scans horizontally at all azimuth angles providing a plan view of the hurricane. A major drawback of this radar is the large vertical beam width (4.1°) that causes inadequate vertical resolution at distances greater than 60-70 km (Marks 1985). The tail radar scans anywhere from 25° ahead to 25° behind the aircraft rotating in the vertical plane at a wavelength of 3.2 cm (X-band). This small wavelength radar suffers from high attenuation (Jorgensen 1984a). Both radars are also subject to the pitch and roll of the aircraft which can distort the reflectivity image. Analysis was undertaken with keen awareness for the sensitivities of the radar. Nearly 1000 tail and LF radar images were processed at the Hurricane Research Division (HRD). The images provide a

continuous view of the TC inner core during and subsequent to RI and are used to calculate net LHR.

In-situ sensors on the aircraft record flight-level temperature, pressure, and humidity at a 1 Hz frequency. The wind is determined as the difference between the true airspeed vector and the actual motion in space measured by GPS and inertial navigation (Black et al. 2002). A complete list of aircraft instrumentation can be found in Jorgensen (1984a) and recent upgrades are mentioned by Aberson et al. (2006).

The two aircraft deployed 82 GPS sondes in Hurricane Guillermo over the two days. On 03 August a last minute decision was made to release GPS sondes in the eyewall. These GPS sondes sampled much tighter thermodynamic and kinematic gradients that provide more detailed information near the circulation center than on 02 August. Figure 3 displays the storm relative location of each GPS sonde used in the analysis. The GPS sondes were developed through a joint effort involving the National Center for Atmospheric Research (NCAR), NOAA, and German Aerospace Research Establishment to replace the ODW. The GPS sondes have a fall rate of $12\text{--}14\text{ m s}^{-1}$ in the lower troposphere and take nearly 4 minutes to reach the ocean surface when deployed at 700 hPa. Temperature, pressure, and humidity sensors sample at a rate of 2 Hz resulting in data every 6-7 m. Table 2 lists the resolution and accuracy of the GPS sonde sensors and a more complete description of the GPS sonde can be found in Hock and Franklin (1999).

2.3 Data Preparation and Quality Control

All of the GPS sonde data were processed through the Atmospheric Sounding Processing Environment (ASPEN) program. This software was developed by NCAR to

accept raw data in the form of AVAPS (Airborne Vertical Atmospheric Profiling System) files. An extensive series of quality control (QC) algorithms were applied to systematically detect data that were likely to be contaminated, and either correct or remove them from the data set.

When processed through ASPEN, each variable was considered separately and passed through outlier checks and smoothing. The one exception was GPS derived winds. The winds were divided into u and v components and both were discarded if one of the two failed a quality control test. ASPEN also corrected for the temperature time lag, a known problem that occurs with the GPS sonde's Thermocap. The program then displayed the raw and QC data in both tabular and graphical form in addition to producing a Skew-T diagram. The percentage of data that was modified by the QC algorithms was also listed. A complete description of QC procedures and further details regarding ASPEN algorithms can be found in the ASPEN User Manual (<http://www.eol.ucar.edu/rtf/facilities/software/aspen/Aspen%20Manual.pdf>).

Occasionally, large portions of the sounding were removed and the profiles were rendered useless. Equipment malfunction, such as a break in satellite connection, and sensor failure, which produce erratic profiles, resulted in the discard of 12 soundings. The remaining 70 soundings underwent additional scrutiny after being processed for analysis. Brief gaps of missing data were populated with linearly extrapolated values for distances less than 300 m or about 20-25 s of fall time. Obviously, meteorological variables do not usually act as linear functions, but it was assumed the linear values are very similar to actual values since the missing data occurs over a small depth. If the missing data exceeds a depth of 300 m then that portion of the profile was not used. The

wind observations had the highest failure rate near the sea surface with 22 of the 70 (31%) containing no data at 10 m. Failure rates were only 10% at 50 m and 7% by 100 m with most of the failures occurring in high winds. Franklin et al. (2003) examined 429 eyewall sondes for 17 hurricanes and found failures to quickly increase below 100 m (Fig. 4). The cause of the failures was believed to be the GPS sonde's inability to maintain communication with GPS satellites.

Despite the application of ASPEN, there remained some questionable corrections, or lack thereof, with the GPS sonde data. A common error found in post ASPEN analysis was a dry adiabatic lapse rate that was saturated (Fig. 5). This error was likely due to the relative humidity sensor remaining wet after having passed through a saturated layer (Bogner et al. 2000). A correction for this error was made by assuming a constant mixing ratio where the temperature follows a dry adiabatic lapse rate. New relative humidity values were then calculated. Biases were also corrected from quality controlled ASPEN data. When the dewpoint and the temperature sensor were very close, and tracked each other nearly perfectly at the moist adiabatic lapse rate, we assumed that the dewpoint is biased low and the layer was actually saturated (Fig. 6). For these cases the dewpoint was increased until the first relative humidity value reached 100%. The correction was then applied to the entire dewpoint profile and new relative humidity values were calculated. Figure 6b shows the new Skew-T diagram after the correction was applied. In all, a total of 23 GPS sondes had some post ASPEN corrections.

Once the data were quality controlled, they were processed through a MATLAB program to produce vertical profiles and storm relative horizontal fields at any desired level from near the sea surface to 4 km altitude. The HRD track of Guillermo, composed

of satellite and aircraft fixes, generates a latitude and longitude pair every 10 minutes and was used to determine the TC position for a given time. Analysis was centered during the mean time between the first and last GPS sonde deployment for each day. Advection of sondes, due to their location and time of deployment, was accounted for to create a composite image of the TC. Thermodynamic calculations follow the work by Bolton (1980). Radial and tangential winds were calculated as follows:

$$v_r = u_{rel} \cos\theta + v_{rel} \sin\theta$$

$$v_t = -u_{rel} \sin\theta + v_{rel} \cos\theta$$

Where $u_{rel} = u_{sonde} - u_{storm}$, $v_{rel} = v_{sonde} - v_{storm}$, and θ is the angle between the GPS sonde and a Cartesian coordinate system aligned along a unit circle.

GPS sonde data were interpolated to constant height intervals of 10 m and a piecewise cubic Hermite interpolation (Fritsch and Carlson 1980) was performed to analyze the fields for each level. This cubic spline method preserved the monotonicity and the shape of the data. Because of coarse horizontal resolution and the assumption of steady-state over the six hours to create the composite, individual thunderstorms or small rainbands cannot be detected. Subjective hand analyses were compared for several variables at different levels and matched well with the cubic spline derived analysis. The cubic spline and compositing technique did, however, produce loose gradients and sharp angles that are not indicative of reality. These images are considered working images. They were not modified except when inadequate sampling of tight gradients near the eyewall occurred. During these instances aircraft data were manually incorporated into the analysis to better represent reality.

Extrapolation of flight-level winds to various altitudes closely followed the work of Franklin et al. (2003) and is presented in Table 3. Most of the extrapolated data covered a small area or depth. Kinematic and thermodynamic data from NOAA aircraft were used to better define the inner core where GPS sondes did not sample the tight gradients of the eyewall. Because the two days had repeatable flight patterns the same six locations of eyewall drops from 03 August were chosen as the locations to bogus data in the eyewall on 02 August. Besides the obvious improvement and a more realistic field, these changes made for more accurate comparisons between the two days plausible.

Finally, a single eye drop on 02 August was utilized for the composite images. Temperature and dewpoint measurements were recorded for the entire descent, but winds below 400 m were lost. Representation of light winds in the eye is crucial to accurately depict the kinematic fields, so the 300 m threshold was violated for this specific case. The 100 m kinematic fields were using the same u and v components last reported near 400 m and were likely very similar to what was observed at 100 m. Figure 7 demonstrates how these adjustments more accurately depict reality.

CHAPTER 3:

REFLECTIVITY STRUCTURE

3.1 02 August

On 02 August tail and LF radar images reveal an asymmetric wavenumber-1 reflectivity structure, with intense quasi-stationary convection in the eastern eyewall (Fig. 8). The first pass through the circulation center reveals an elliptical eye with an eyewall open on its west side (Fig. 8a). Throughout the mission reflectivity gradually increases within the inner core and a more circular, smaller, and complete eyewall is sampled by the aircraft near mission's end (Fig. 8b). However the asymmetric eyewall structure is still present and the most intense reflectivity remains in the east eyewall. Similar reflectivity configuration and behavior was observed by Black et al. (2002) when they examined two TCs embedded in shear $> 8 \text{ m s}^{-1}$. On this day Guillermo is embedded in northerly shear near 7 ms^{-1} and the intense convection is located left of the downshear vector. Model studies (e.g., Frank and Ritchie 2001) suggests that shear induced differential vorticity advection with height is responsible for the asymmetric structure.

Reflectivity tops regularly reach 14 km in the eastern eyewall, contrasted with tops in the west eyewall near 11 km (Fig. 9). Despite an increase of precipitation within the inner core, the eyewall asymmetry remains prevalent during the entire sampling period. During the final pass through the TC, a vertical cross section of the reflectivity field depicts echo tops more than 6 km higher in the east-northeast eyewall than in the west-southwest eyewall (Fig. 9b).

Jordan (1952) and Weatherford and Gray (1988) found little correlation between eye size and intensity. There is, however, a correlation between contracting eyes and

intensification (Jordan 1961, Holliday and Thompson 1979, Willoughby et al. 1982, Jorgensen 1984a, Weatherford and Gray 1988, Bosart et al. 2000). Willoughby et al. (1982) documented the contracting eyes of Hurricane Anita (1977), Hurricane David (1979), and Hurricane Allen (1980) as they intensified. These TCs were intense, symmetric, and had established CEs. In contrast, Guillermo is an asymmetric TC and the eye diameter reduction is not a result of CEs or uniform contraction.

The 240 km x 240 km LF reflectivity images obtained from the 700 hPa aircraft are used to measure the eye diameter of Guillermo, defined by the 29 dBZ contour, on 02 August. Seventy-nine north-south and east-west measurements, taken through the approximate geometric center of the eye, are plotted in Figure 10. The mean eye diameter is just over 55 km at the start of the mission. The large range of eye diameter measurements that follow are attributed to the rotation of an elliptical shaped eye in association with the periodic closure of the west eyewall. Fluctuations in the mean eyewall diameter for the most part mimic those of the east-west measurements. Less variability is observed during the second half of the mission when the eye is more circular. A decrease of some 15 km of the mean eyewall diameter is observed from the first to last pass of the mission.

At times during the rapid deepening on 02 August, convection from Guillermo's northern eyewall spirals into the eye in an attempt to establish a nearly complete, closed eyewall. When successful, the eye diameter is quickly reduced. LF reflectivity images capture this process (Fig. 11). During the eye diameter reduction, extrapolated surface pressures from the 700 hPa aircraft indicate a 6 hPa decrease from the 4th (20:42 UTC) to the 6th pass (21:54 UTC). During the 5th pass (21:19 UTC), the northern eyewall spirals

into the eye closing off the west half of the eye. The intruding band of eyewall convection contains echo tops 12 km high and 37 dBZ reflectivity values near the surface (Fig. 12). These values are similar to those found in the east-northeast eyewall. 700 hPa aircraft data reveals an eye-like thermodynamic profile on both sides of the intruding band with dewpoint depressions after the passage of the band similar to those in the central eye before the aircraft nears the band (Fig. 13). In time, dry air and the band of convection mix. Eventually the eye's environment is too hostile and leads to the band's demise, resulting in a larger, open eye. However, this mixing contributes to the moistening of the low level eye. A GPS sonde deployed in the eye during the last pass shows the lower eye was closer to saturation and contains higher θ_e than the previous eye drop during the middle of the mission. Eastin (2005a,b) argues that the low level eye is a vital source region for buoyant updrafts in the eyewall and that advection of high θ_e from the eye into the eyewall contributed to the intensification of Guillermo.

Another successful closure of the eye occurs near the end of the mission. From the 9th (23:33 UTC) to 10th (00:04 UTC) pass (31 min) the mean eye diameter reduces nearly 10 km and extrapolated surface pressure decreases 2 hPa. Because the eyewall does not uniformly contract, but rather spirals into the eye, the eye diameter reduces in pulses over very short periods. These abrupt eye diameter reductions coincide with rapid surface pressure falls. These two instances account for two-thirds of the 12 hPa drop during the mission.

3.2 03 August

On 03 August the first pass through the circulation center reveals a more circular eye with a nearly complete eyewall (Fig. 14a). However, a similar shear vector persists

and the wavenumber-1 reflectivity pattern, with the most intense convection in the east eyewall, is still observed. The mean eye diameter is 10 km smaller than the previous day and evolves slowly, expanding by a few km over the sampling period. The final pass on 03 August reveals that reflectivity again increases within the inner core and the most intense convection is confined to the east eyewall (Fig. 14b). Tail radar reflectivity images mirror the previous day. Figure 15 displays reflectivity values > 37 dBZ at 6 km at various times of the mission. The intense convection attenuates the radar beam and results in a lack of reflectivity over the eastern side of the TC.

3.3 Reflectivity Comparison

Tail radar is used to examine 16 azimuths of eyewall echo tops on 02 August and 14 azimuths on 03 August (Fig. 16). The timing of the fore/aft scanning technique of the tail radar was such that the north-northeast and west-southwest sections were not sampled on 03 August, even though the same flight pattern was flown. Echo tops are very similar for most locations on both days. The north and east regions contain the highest echo tops that occasionally reach above 15 km. The daily average of all azimuths indicates echo tops were essentially the same, less than a half kilometer difference. The steadiness of the reflectivity structure is confirmed with net LHR calculations.

3.3.1 Net Latent Heat Release

Latent energy release is the primary energy source for a TC. Rainfall, a measure of net LHR, has been shown in previous studies to be a reliable gauge of TC intensity. More rainfall is associated with intense TCs (Adler and Rodgers 1977, Rodgers and Adler 1981, Cervený and Newman 2000). Additionally, these studies emphasize that higher rainfall rates concentrate near the TC center during intensification. Marks (1985)

examined aircraft radar of Hurricane Allen (1980) for several days over a 111 km radius from the TC center. No apparent relationship was observed between intensity and daily changes of net LHR, but a maximum of net LHR occurred 2 days prior to Allen's maximum intensity. Maximum net LHR preceding maximum intensity by a day or more has been detected by other investigations as well. Rodgers and Adler (1981) monitored the net LHR trends for 21 TCs and found the time of maximum TC intensity to lag 1-2 days behind the time of maximum net LHR. Super Typhoon Paka (1997) also had a LHR maximum a day prior to maximum intensity (Rodgers et al. 2000). Most prior investigations examining the net LHR of TCs have utilized satellite-derived measurements, which have to be calibrated to estimate rain rates. Others have taken a broader approach with periodic observations of a TC over days resulting in coarse temporal resolution. This study takes advantage of numerous measurements over a short period during and after RI to examine the magnitude and tendency of net LHR.

Twenty 120 km x 120 km LF radar reflectivity images from the 700 hPa aircraft are used to calculate net LHR on 02 and 03 August. The reflectivity images are taken during each pass through the eye of Guillermo when the aircraft is very near the circulation center and has an unobstructed view of the eyewall. This serves as a standard time when the radar has a similar view of the TC with minimal attenuation and beam filling compromises. The reflectivity images are composed of 15 standard ranges of 2-3 dBZ increments. Given that beam filling becomes a serious problem beyond 60-70 km (Marks 1985), the reflectivity image is cropped to only include reflectivity values within a 60 km radius from the aircraft. This includes the eye, eyewall, and segments of adjoining rainbands on both days. The images are imported into GNU Image

Manipulation Software 2.2. This software determines the total pixel count of the individual 15 standard dBZ ranges, i.e., 15 different rain rates. Since the total pixel count and area of each image are known, the specific area for each rain rate can be estimated with accuracy. The <15 dBZ range is excluded from the calculation since it produces a near negligible contribution to net LHR and some of the rain is assumed to have evaporated before it reaches the surface. The Rosenfeld tropical Z-R relationship (Rosenfeld et al. 1993) and the mean dBZ value for each standard dBZ range are utilized to calculate rain rates. The Rosenfeld Z-R relationship compares well with rain gauges for convective-maritime rain regimes, as well as continental squall lines at close ranges (Rosenfeld et al. 1993). As a comparative measure the Jorgensen and Willis (1982) Z-R relationship is used to calculate rain rates. This relationship produces lower rain rates, especially for greater dBZ values. The Jorgensen and Willis net LHR values are nearly 50% less than when the Rosenfeld relationship is applied. Net LHR is calculated using

$$\text{Net LHR} = L\rho \iint A_{\text{dBZ}} \text{RR}_{\text{dBZ}} dA d\text{RR}$$

Where L is the latent heat of condensation ($2.5 \times 10^6 \text{ J kg}^{-1}$), A is the area of a particular rain rate, RR , and ρ is the density of rain (assumed to be $1.0 \times 10^3 \text{ kg m}^{-3}$).

The averages of the 10 net LHR calculations on each day are $3.4 \times 10^{13} \text{ W}$ on 02 August and $4.1 \times 10^{13} \text{ W}$ on 03 August (Fig 17). The net LHR on 03 August, when the TC is more than 25 hPa deeper, is 21% ($7.18 \times 10^{12} \text{ W}$) greater than the previous day. The greater net LHR associated with the more intense TC is in agreement with previous studies. On 02 August Guillermo deepens some 12 hPa from the first to last pass through the eye. However, there is no gradual net LHR increase during the sampling period, in

fact, a slight decrease is evident. The net LHR calculations rely on the always evolving inner core reflectivity structure and changes from pass to pass can be detected. Despite this ability the net LHR trend is essentially steady during RI on 02 August.

Rodgers et al. (1998) used satellite based microwave sensors to estimate net LHR for Hurricane Opal (1995) using a radius similar to the one used in this study. Although measurements were hours apart, they were frequent enough to capture large-scale temporal net LHR changes. Two spikes in net LHR ($\sim 6.5 \times 10^{13}$ W) were measured during the study. The first was at the onset of RI and the second was observed at the time of Opal's lowest surface pressure. In between spikes, when Opal was undergoing RI, net LHR decreased to around 4.0×10^{13} W. During this time Opal's eye became encircled by deep convection and almost closed off (Bosart et al. 2000). Guillermo behaves in a similar fashion during RI as convection continually attempts to close off the west eyewall. Perhaps a more axisymmetric eyewall structure is a more efficient method of warming a specific region of the inner core. On 03 August Guillermo has a more complete eyewall and greater amount of net LHR.

The reduction of Guillermo's eye diameter on 03 August should impact the net LHR calculations. A smaller eye reduces the eyewall circumference, thus reducing the area of the most intense reflectivity, assuming the width of the eyewall remains constant. Marks (1985) found that a reduction in eye diameter was roughly balanced by the increased rain rate in the eyewall. Focus on the specific rain rates and their contribution to Guillermo's net LHR reveals a 58 % increase in area for the 35-40 dBZ range from 02 to 03 August. The most intense rain rates (> 43 dBZ) actually decrease in area. In

addition, the <15 dBZ area decreases by nearly half on 03 August because of higher rain rates over the west inner core and a smaller eye on 03 August.

CHAPTER 4:

KINEMATIC STRUCTURE

4.1 Total Winds

4.1.1 02 August

The 100 m altitude total wind field on 02 August is presented in Fig. 18a. To compensate for the lack of GPS sondes in the eyewall, aircraft in-situ measurements from near 700 hPa have been extrapolated to various levels following the work of Franklin et al. (2003). Maximum total wind speeds exceed 50 m s^{-1} over the north and east eyewall. Total winds in west eyewall are more than 5 m s^{-1} less. The region from 75 km out to 300 km from the circulation center, referred to hereafter as the outer core, also has a marked asymmetry. The 25 m s^{-1} contour extends over 225 km from the circulation center in the northeast quadrant, but only extends out some 75 km to the southwest. Total winds $< 10 \text{ m s}^{-1}$ are observed 250 km southwest of the TC center.

At 1.5 km altitude maximum total wind speeds exceed 60 m s^{-1} in the northeast inner core (Fig. 18b). Total winds have increased noticeably at this level in all but the southwest outer core. Speeds there are similar to those observed at 100 m. Outer core total winds in the northeast quadrant are nearly double those in the southwest at similar radii. In contrast, a more symmetric outer core is analyzed at 4 km altitude (Fig. 18c). However, a slight asymmetry exists. The 25 m s^{-1} contour extends further east (150 km) from the circulation center than west (115 km). Over the far western outer core total winds remain relatively weak ($< 15 \text{ m s}^{-1}$).

4.1.2 03 August

Maximum sustained total winds are near 65 m s^{-1} at 100 m on 03 August (Fig. 19a). Inner core total wind speeds $> 40 \text{ m s}^{-1}$ are arranged in a circular fashion around the eye. Sampling of the southwest quadrant on 03 August extends only to 150 km from the circulation center due to multiple GPS sonde failures. However, it can still be seen that the outer core is more symmetric than the previous day. The 25 m s^{-1} contour is analyzed roughly 150 km northwest and southeast of the circulation center. At 1.5 km total winds in the north and east eyewall exceed 60 m s^{-1} (Fig. 19b), but the southwest eyewall struggles to reach 50 m s^{-1} . The outer core is less symmetric than at 100 m. The 25 m s^{-1} contour extends twice as far from the circulation center over the eastern half of the TC than the western half. At 4 km, the inner core total wind field becomes more asymmetric with decreasing radii from the circulation center (Fig. 19c). The eyewall remains asymmetric with maximum total winds near 62 m s^{-1} . The outer core field still exhibits an asymmetric structure. The highest winds ($25\text{-}30 \text{ m s}^{-1}$) extend 225 km southeast from the circulation center.

4.1.3 Total Wind Speed Differences

The difference in total wind speed at 100 m, 03 August minus 02 August, is presented in Figure 20a. The area within a 25 km radius of the circulation center is removed to conceal extreme differences near the eye that are a result of the cubic spline. Inner core 100 m total wind speeds increase on 03 August in all but the northeast quadrant, where they remain unchanged or weaken slightly. The greatest increase (20 m s^{-1}) occurs 50 km north-northwest of the TC center. Much of the southern outer core total winds increase at least 5 m s^{-1} . More intriguing is the decrease of total wind over

the north and east portions of the outer core despite the RI. Roughly 100-125 km north of the TC center total winds are more than 10 m s^{-1} weaker on 03 August. Similar observations have been previously documented by Weatherford and Gray (1988) who noted that changes of the inner core intensity appear at times to occur almost independently of outer radius wind changes. They established that a TC's outer core (111 km - 275 km) is very weakly correlated to TC intensity and can sometimes behave counterintuitively, as it is in this case. However, Croxford and Barnes (2002) examined the 65 km to 140 km area for 18 TCs and found the tangential wind field to become more homogenized in conjunction with intensification, with no particular quadrant stronger than another for more than 12 h.

Total winds over the northwest and southeast portions of the inner core increase with a maximum of 15 m s^{-1} 75 km southeast of the TC center at 1.5 km (Fig. 20b). The north and east outer core regions still decrease over a similar area observed at 100 m, but the magnitudes are weaker ($2\text{-}6 \text{ m s}^{-1}$). By 4 km almost the entire southern half of the inner core increases more than 5 m s^{-1} (Fig. 20c). Much of the outer core remains unchanged or increases up to 5 m s^{-1} .

Aircraft data taken near 700 hPa reveals Guillermo's inner core structure remains asymmetric between days. Total wind speeds are $7\text{-}10 \text{ m s}^{-1}$ greater in the north-northeast eyewall than the south-southwest eyewall (Fig. 21). Despite the difference in intensity between the two days, and a more complete eyewall reflectivity structure on 03 August, Guillermo's inner core total winds fail to homogenize. Clearly an asymmetric TC can undergo RI and the resulting more intense TC is not required to have a more symmetric inner core wind field.

4.2 Tangential Winds

Extrapolated aircraft data from near 700 hPa is used to better resolve the inner core tangential wind field. The average ratio of tangential wind to total wind observed on 03 August is applied to the 02 August fields. Tangential winds in the eyewall are taken as 85%, 90%, and 95% of the total wind field at heights of 100 m, 1.5 km, and 4 km respectively. The purpose of the forged data is to provide a much more realistic tangential wind field than what is observed without the correction near and in the eyewall.

4.2.1 02 August

At 100 m on 02 August the eastern half of the eyewall contains maximum tangential winds near 45 m s^{-1} (Fig. 22a). Inner core tangential winds gradually decrease with increasing radius from the TC center and develop a symmetric outer core field within 150 km of the circulation center. Beyond 150 km tangential winds over the west and southwest portions of the TC begin to decrease at a faster rate than what is observed over eastern sections. At 250 km northeast of the circulation center tangential winds are near 18 m s^{-1} and tangential winds are approximately 12 m s^{-1} southwest of the TC center at a similar radius. At 1.5 km maximum tangential winds $> 55 \text{ m s}^{-1}$ are located in the north-northeast eyewall of Guillermo (Fig. 22b). The inner core is asymmetric. Tangential winds 75 km east of the TC center are 10 m s^{-1} greater than compared to the west. The outer field is also asymmetric with 33 m s^{-1} tangential winds in the northeast quadrant and 20 m s^{-1} tangential winds in the southwest quadrant 150 km from the TC center. The inner core tangential wind field remains asymmetric at 4 km with maximum winds near 50 m s^{-1} in the east eyewall (Fig 22c). Tangential winds in the west eyewall

range from 40–45 m s^{-1} . Greater tangential wind speeds extend further south from the inner core and an asymmetric outer core exists. At 150 km from the TC center tangential winds in the southeast quadrant reach 30 m s^{-1} . Northwest quadrant tangential winds are approximately 18 m s^{-1} at the same distance.

4.2.2 03 August

At 100 m on 03 August maximum tangential winds of 60 m s^{-1} are located in the north and south eyewall (Fig. 23a). The 35 m s^{-1} tangential wind contour is circular and extends along the periphery of the inner core. The outer core contains small variations, especially beyond a 150 km radius from the TC center. Tangential winds beyond this radius range from 15–20 m s^{-1} . At 1.5 km the entire tangential wind field, excluding the eye, contains values greater than 15 m s^{-1} (Fig. 23b). Tangential winds at the east eyewall are nearly 12 m s^{-1} greater than the west eyewall. Little variability over the outer core beyond a 125 km radius from TC center is again observed at this level. Outer core tangential winds beyond 150 km from the TC center generally range from 20–25 m s^{-1} . At 4 km maximum tangential winds near 60 m s^{-1} are located in the southwest and northeast portions of the eyewall (Fig. 23c). Despite the eyewall asymmetry, the inner core becomes more symmetric with increasing radius from the eye. Outer core tangential winds are more asymmetric at this level than at 1.5 km. Tangential winds 200 km southeast from the circulation center near 28 m s^{-1} and at a similar distance, tangential winds in the northwest quadrant approach 20 m s^{-1} .

4.2.3 Tangential Wind Speed Differences

The 100 m tangential wind difference field is presented in Figure 24a. Tangential winds increase throughout the inner core, especially southeast and northwest of the eye

where values increase more than 15 m s^{-1} . The southern region of the outer core also shows an increase, especially for distances greater than 150 km south of the circulation center where the increase exceeds 10 m s^{-1} . Much of the remaining outer core remains unchanged or weakens during RI. The largest decrease of 6 m s^{-1} is analyzed 100 km north-northeast of the TC center. At 1.5 km tangential winds in and near the eyewall increase at least 5 m s^{-1} , except for a small region of the southwest eyewall where winds decrease slightly. The largest increases (15 m s^{-1}) are found roughly 75 km southeast of the TC center and in the small portion of the northwest eyewall (Fig. 24b). Much of the outer core does not change. A small decrease of less than 5 m s^{-1} is observed roughly 100 km east of the TC center. South and west portions of the outer core contain increased values $< 5 \text{ m s}^{-1}$. At 4 km much of the inner core continues to show an increase of at least 5 m s^{-1} (Fig. 24c). Elsewhere there is no pattern of any consequence, save for a decrease of 10 m s^{-1} 100 km southeast from the circulation center.

4.3 Radial Winds

4.3.1 02 August

Without GPS sondes sampling the eyewall on 02 August inflow values near the eyewall are underestimated at 100 m. As a first order correction, radial wind values near the inner core will be used to forge data at the eyewall at 100 m and 1.5 km on 02 August and at 4 km on both days.

The 100 m radial wind field on the 02 August is essentially all inflow (Fig 25a). The entire eyewall region ($r \approx 25 \text{ km}$) is surrounded by at least 10 m s^{-1} inflow. A large region of maximum inflow (16 m s^{-1}) occupies portions of the east and southeast inner core. Large inflow values extend beyond the inner core and still exceed 12 m s^{-1} over

250 km south-southeast of the circulation center. Outer core inflow values over the southeast quadrant are more than five times greater than the $2\text{--}3\text{ m s}^{-1}$ inflow analyzed in the northwest quadrant. At 1.5 km outflow and inflow values of similar magnitude are aligned opposite to each other across the circulation center (Fig. 25b). Outflow is analyzed within 25 km of the west eyewall. The northwestern outer core has undergone substantial change and contains outflow $> 10\text{ m s}^{-1}$ 100 km from the circulation center. Maximum inflow values near 10 m s^{-1} are located in the southeast inner and outer core. The inflow maximum begins to rotate anticyclonically with height such that inflow is found in the southwest quadrant by 2.5 km (not shown). This rotation continues and by 4 km maximum inflow values approaching 10 m s^{-1} are well established just beyond the southwestern inner core and weak outflow now covers nearly the entire eastern half of the TC (Fig. 25c). Marks et al. (1992) documented a similar radial flow transition in Hurricane Norbert (1984). Additionally, several other observational studies (Willoughby et al. 1982, Jorgensen 1984b, Marks and Houze 1987, Marks et al. 1992, Black and Holland 1995, Black et al. 2002) have observed asymmetric radial wind fields with inflow aligned with outflow across the circulation center at various radii. This arrangement of outflow at 1.5 km situated under inflow at 4 km is correlated with a lack of convective cells over the western portion of Guillermo near the start of the mission (Fig. 26). Over this region precipitation is primarily stratiform and reflectivity values seldom exceed 25 dBZ.

A height-azimuth cross section of radial wind 100 km from the circulation center is presented in Fig. 27. At this distance there are several GPS sondes that provide a clear illustration of the radial flow. The radial structure in the lowest 1.5 km on 02 August

reveals a focused channel of strong inflow ($> 10 \text{ m s}^{-1}$) in the southeast quadrant. Inflow $> 15 \text{ m s}^{-1}$ extends from sea surface to 400 m and values exceed 10 m s^{-1} above 1.5 km. At the north and northwestern azimuths inflow below 100 m is less than 5 m s^{-1} . Outflow as low as 500 m is observed over the western portions of Guillermo.

4.3.2 03 August

The inclusion of GPS sondes in the eyewall on 03 August provides a more complete representation of the radial wind field within and around the inner core. At 100 m inflow is axisymmetric (Fig. 28a). Inflow values exceed 20 m s^{-1} around the eye and the only outflow at this level is found in the eye. Beyond 125 km from the circulation center inflow ranges from $3\text{-}5 \text{ m s}^{-1}$. At 1.5 km outflow is observed within the inner core (Fig. 28b). In stark contrast to the 100 m field, strong outflow ($> 10 \text{ m s}^{-1}$) is near the eyewall. All 6 of the eyewall GPS sondes exhibit outflow below 1 km resulting in high shear values up to of $40.0 \times 10^{-3} \text{ s}^{-1}$ in lowest 1 km. The outflow from the eyewall combines with a well established region of outflow over the northwestern outer core ($\sim 4 \text{ m s}^{-1}$). Once again, outflow and inflow are aligned opposite to each other across the circulation center. Inflow values of $6\text{-}8 \text{ m s}^{-1}$ are analyzed over the eastern and southern outer core. Anticyclonic rotation of the maximum inflow values with height is again observed, but to a lesser extent. At 4 km a wavenumber-1 pattern is apparent. Radial flow in the northeast outer core is of similar, but opposite magnitude to flow in the southeast outer core (Fig. 28c).

Figure 29 displays a height-azimuth cross section of radial wind 100 km from the circulation center. A layer of strong inflow is analyzed for all but the north azimuth. Rather than one focused region, inflow is spread uniformly on 03 August below 1 km.

Inflow $> 5 \text{ m s}^{-1}$ extends above 1.5 km over the south and east azimuths. Strong inflow fails to survive above a kilometer. Inflow switches to outflow over the northern half of the TC near 900 m altitude.

Just beyond the perimeter of the eyewall, 55 km from the circulation center, an increase in both inflow and outflow is observed when compared to the 100 km radius (Fig. 30). All azimuths now contain a layer of strong inflow up to 500 m. Regions of inflow $> 20 \text{ m s}^{-1}$ are observed below 250 m. Outflow is analyzed below 750 m over the north portion of the eyewall. By 1.5 km outflow is observed in all but the east and southeast sectors and exceeds 10 m s^{-1} for the northern sector above 1200 m. Rather than increase the depth of the inflow layer, the need for greater inflow near the eyewall is achieved by an increase of values near the surface. Figure 31, an examination of four GPS sondes along a constant azimuth, captures the evolution of the radial flow with decreasing radius from the circulation center. The GPS sondes were deployed 135 km to 20 km north of the TC center. They reveal an increasing inflow rate, in conjunction with a diminishing thickness of the inflow layer, with decreasing radius from the circulation center. Outflow increases above the inflow layer with decreasing radius as well. This outflow remains $> 5 \text{ m s}^{-1}$ near the eyewall to regions far beyond the inner core.

CHAPTER 5:

THERMODYNAMIC STRUCTURE

5.1 Temperature

Flight-level temperatures from the 700 hPa aircraft are extrapolated at all levels on 02 August and at 4 km on 03 August to better resolve the inner core temperature fields in the eyewall. The eyewall region is assumed saturated, so the moist adiabatic lapse rate was applied for the extrapolation. Flight-level temperatures were brought down (up) a moist adiabat for the 1.5 km (4 km) fields. The dry adiabatic lapse rate was applied from 200 m above the surface for the 100 m field, a similar location where eyewall GPS sondes began drying out on 03 August.

5.1.1 02 August

Guillermo's temperature field provides insight into the impact of the asymmetric structure described in previous sections. Temperatures at 100 m range from 24.0 °C to near 28 °C with warmest temperatures located over the northern fringe of the analysis on 02 August (Fig. 32a). A large area of warm air (~27 °C) is situated over the southwest outer core 100-225 km from the TC center. The coolest temperatures are collocated with the shield of stratiform precipitation and embedded rainbands, observed by radar, over the eastern outer core. The most intense convection in the eastern inner core matches well with the location of the coldest temperatures and may be an indication of downdrafts and evaporational cooling. The cooler air within the inner core matches the findings of Cione et al. (2000) and Barnes and Bogner (2001). These studies utilize buoy and ODW data, respectively, to show that low level inflow is not isothermal and the greater difference between SST and surface air temperature occurs within the rainband region,

primarily due to a reduction of the surface air temperature. This is especially true when SST is at least 27 °C.

By 1.5 km much of the western half of the TC is at least 0.75 °C warmer than the eastern half (Fig. 32b). The coldest regions, with temperatures near 17 °C, are located 125 km north and 100 km southeast of the TC center. The spoke of high temperature (20.3 °C) that extends 100 km southwest of the TC center is only 0.5 °C cooler than what is observed in the eye. The warmer temperatures over the western outer core are believed to be a result of subsidence.

Average vertical velocity measurements (1 Hz) from the 700 hPa aircraft, for a distance 55 km to 80 km from the circulation center, were -0.07 m s^{-1} over the southwest quadrant. All other quadrants contained positive vertical velocities. The southeast, northeast, and northwest quadrant had average vertical velocities of 0.36 m s^{-1} , 0.72 m s^{-1} , and 0.04 m s^{-1} respectively. The 55 km to 80 km distance was selected to exclude the eyewall vertical velocities and obtain a better sense of the ambient vertical velocity field beyond the eyewall. Four flight legs were used to obtain the average in each quadrant and no bias of the vertical velocity measurements appeared to develop during the mission. At 4 km, the eye contains the warmest air of 12 °C (Fig 32c.). With the exception of the warm air just north of the inner core, the outer core contains weak gradients with near uniform temperatures of 5 °C.

5.1.2 03 August

On 03 August Guillermo's eye temperature at 100 m exceeds 28.0 °C and is surrounded by an eyewall that is 3-3.5 °C cooler (Fig. 33a). The cool inner core temperatures now surround the eye. This is attributed to a more complete eyewall

reflectivity structure observed from radar. Outer core temperatures less than 26 °C are again collocated with the precipitation field over the eastern half of the TC. The western outer core is roughly 0.5 °C warmer than the eastern outer core beyond 125 km from the circulation center. At 1.5 km the maximum eye temperature is 21.2 °C (Fig. 33b). The eastern outer core exhibits vertically aligned contours resulting in a smooth analysis. The northwestern quadrant of the outer core is 1.0 °C -1.5 °C warmer than the southeast quadrant at similar radii. Temperatures over the western inner core, near the eyewall, are a degree warmer than the eastern inner core. By 4 km, a maximum of 16 °C is located in the eye and very tight gradients exist in the inner core (Fig. 33c). The outer core temperature contains little variability. Temperatures range from 5 °C in the southeast to near 6.5 °C north and northeast of the TC center.

5.1.3 Temperature Differences

The greatest decrease of temperature (1 °C) at 100 m is observed in the southwestern quadrant of the inner and outer core (Fig. 34a). Elsewhere in the inner core temperatures increase more than 0.5 °C from 02 August to 03 August. Outer core temperatures increase by more than 0.5 °C, except for the southwest quadrant and a small region beyond 200 km north of the circulation center, where temperatures cooled up to 0.5 °C. The greatest increase, more than 2 °C, occurs 250 km south of the TC center. The 1.5 km temperature difference field reveals an area of warming > 1 °C, with an embedded maximum of over 2 °C, over the northwest sector of the outer core 50-75 km from the TC center (Fig 34b). Warming is also observed just beyond the eastern periphery of the inner core. South and east portions of the outer core, beyond 150 km, remain unchanged or cool 0.75 °C. A 1.5 °C decrease is analyzed 100 km southwest of

the TC center. The eye temperature shows no change, but the north and east eyewall warm at least 1 °C. At 4 km much of the outer core warms 0.5 °C – 1.5 °C (Fig. 34c). An increase near 2 °C is located over 175 km north of the TC center. A decrease, no more than 0.5 °C, is observed over 200 km south and northeast of the TC center. Cooling up to 1 °C occurs near the southeastern and south eyewall. The rest of the eyewall region remains unchanged or warms less than 1 °C. A decrease of temperature (~0.25 C) is evident in the northwestern inner core beyond the eyewall region. The eye is shown to warm by 3.5 °C at 4 km. Figure 35 illustrates this warming in a more obvious manner and makes use of all eye drops over the two days. Below 2.5 km the temperature remains the same.

5.2 Equivalent Potential Temperature

5.2.1 02 August

Flight-level data are used to interpolate θ_e at all levels on 02 August to better resolve the inner core near the eyewall. At 100 m on 02 August, the θ_e field consists of a maximum value near 368 K with values steadily decreasing radially outward from the eye within a 100 km radius from the circulation center (Fig. 36a). Similar θ_e distribution has been previously well documented (Hawkins and Imbembo 1976, Willoughby et al. 1984, Jorgensen 1984b, Eastin 2005ab, Schneider and Barnes 2005). Beyond this radius, uniform θ_e values range from 348 K – 351 K, except south of the TC center, where values are near 354 K. A swath of relatively high θ_e extends outward from the inner core to over 100 km south-southeast of the circulation center. GPS sonde 140 produces a local minimum value of θ_e at the southwestern border of the inner core. This minimum is a result of a thin layer of dry air at 100 m. By 150 m the high θ_e region is much more

continuous and covers the entire southern half of the inner core (not shown). A similar structure is noted at 1.5 km with an increase in values over the western outer core (Fig. 36b). Values of θ_e near 346 K still extend over 200 km south of the TC center. Outer core θ_e values, 150 km east of the circulation center, range from 340-342 K. An asymmetric distribution of θ_e is found within the inner core. Values greater than 353 K extend 50 km south of the circulation center, but only 25 km to the north. At 4 km the θ_e eye value of 356 K gradually decreases to a value near 345 K at the periphery of the inner core. Beyond a radius of 100 km from the TC center, the outer core shows small variability with values of 340 K-342 K (Fig. 36c). The northwest region of the inner core contains θ_e values 3 K more than the rest of the inner core at similar radii.

5.2.2 03 August

The 100 m θ_e field on 03 August ranges from 350 K with a maximum value of 377 K in the eye (Fig. 37a). The inner core contains tight gradients, with a 12 K increase of θ_e within a 50 km radius of the circulation center. The outer core field has background values of 355 K-357 K, with the exception of a roughly 100 km wide zone of relatively low θ_e (~350 K), oriented southeast to northwest, 75 km northeast of the TC center. Dewpoints in this region range from 21 °C - 22 °C, the lowest in the 100 m analysis. In comparison, eyewall dewpoints are near 25 °C. Downdrafts may be partly responsible for the low values of θ_e . At 1.5 km, the inner core still contains tight gradients with a maximum value (372 K) in the eye (Fig. 37b). The low θ_e zone 75 km north of the TC center is still analyzed, but covers a much smaller area. The eastern outer core θ_e values range from 344 K to 350 K with higher values (350 K to 355 K) over the western outer core. Flight-level data are used to interpolate θ_e within the inner core at 4 km, where the

maximum value of θ_e in the eye has decreased to 360 K (Fig 37c). The inner core gradients have relaxed and a 6 K increase of θ_e is analyzed over a 50 km radius of the circulation center. The outer core field has θ_e values ranging from 340 K to 346 K. The highest outer core values extend well beyond 200 km south and southeast of the TC. The minimum value is located almost 200 km north of the circulation center.

5.2.3 Equivalent Potential Temperature Differences

The greatest increase of θ_e at 100 m, more than 10 K, occurs far from the inner core in a band 150 km southeast and east of the TC center (Fig. 38a). An increase of at least 2 K is observed over the entire eyewall region, but the increase over the northern eyewall is three to four times greater than the southern eyewall. The northwest and southeast portions of the inner core also contain increases beyond 50 km from the TC center, but the remaining regions beyond 50 km show little change or a 1-3 K decrease. A 10 K increase is observed 75 km northwest of the circulation center. At 1.5 km an increase of 10 K occurs in the eye and eyewall region (Fig. 38b). The band of increased θ_e 150 km southeast and east of the TC center is still discernable, but increases are in the 4-6 K range, half of what was observed at 100 m. The increase 100 km northwest of the TC center is again detected at 1.5 km. Increased θ_e values are observed for much of the outer core with the exception being a 6 K decrease 200 km south of the TC center. The 4 km difference field contains a swath of increased θ_e , more than 5 K, that extends 150 km south of the TC center (Fig. 38c). The eyewall region also increases some 5 K, and the eye increases 3-4 K. A region of little change or small decrease extends from 250 km north of the circulation center down to a maximum decrease of 4 K 75 km west of the TC center.

CHAPTER 6:

SUMMARY

6.1 Conclusions

NOAA aircraft sampled Hurricane Guillermo over the eastern North Pacific during rapid intensification on 02 August and repeated their flight patterns the following day when Guillermo was 25 hPa deeper, but steady-state. Eighty-two GPS sondes were deployed within 300 km of the hurricane over the two days. The GPS sonde data were quality controlled and 70 GPS sonde profiles with sufficient data were used in the analysis. Data from these GPS sondes were treated with a cubic spline to develop horizontal fields from near the surface to 4 km. Tail and lower fuselage radar captured the evolution of the inner core on both days. Several thermodynamic and kinematic changes, some unexpected, were documented. From 02 August to 03 August the 200–850 hPa shear calculated over a radius 200–800 km from the TC center decreased almost 3 m s^{-1} and SST decreased less than $1.0 \text{ }^{\circ}\text{C}$. The synoptic environment varied little during early August and did not provide any clear signals that rapid intensification would occur.

A quasi-stationary wavenumber-1 reflectivity pattern, with intense convection confined to the east eyewall, was observed on 02 August when Guillermo deepened at a rate of 2 hPa h^{-1} . During the first half of the 02 August mission the western outer core contained stratiform precipitation and reflectivity values seldom exceeded 25 dBZ. An oval shaped eye, open on its west side, occasionally closed when eyewall convection wrapped into the eye from the north and reduced the eye diameter. Extrapolated surface pressures from a NOAA aircraft indicated that pulses of rapid deepening occurred in

conjunction with the eye diameter reductions. Eventually, the convection in the eye eroded and the process was repeated. The sudden change in the configuration of eyewall convection produced an immediate pressure decrease. This suggests that the rapid intensification is a response to inner core processes.

On 03 August a circular eye with a 10 km smaller diameter was observed. However, the wavenumber-1 pattern persisted with the greatest reflectivity values in the east eyewall. Mean eyewall echo tops were essentially the same on both days, ranging from 16 km in the northern eyewall to 12 km in the western eyewall. Net latent heat calculations over a 60 km radius from the TC center revealed a 21% increase from 02 to 03 August. Although Guillermo deepened some 12 hPa from the start of the mission on 02 August, net latent heat release calculations on this day were essentially steady. Reflectivity > 43 dBZ decreased in area on 03 August, but the 35-40 dBZ range increased 58%. These findings indicate that more net latent heat within the inner core is associated with more intense TCs.

Tangential and total winds increased more than 15 m s^{-1} between missions and the increase was confined predominately to within 75 km of the circulation center. Beyond 100 km north of the TC center tangential and total winds changed little or decreased up to 10 m s^{-1} at 100 m altitude. Aircraft data near 700 hPa identified an asymmetric total wind structure in the eyewall on both days. Despite the rapid intensification eyewall winds failed to homogenize and wind speeds were nearly 10 m s^{-1} higher in the northeast eyewall when compared to the southwest on 03 August.

On 02 August an asymmetric radial wind field at 100 m altitude consisted of an inflow maximum (16 m s^{-1}) in the southeast quadrant, measured 75 km from the TC

center. This inflow maximum was 4-5 times greater than the remaining quadrants. The inflow layer extended above 1.5 km in the southeast quadrant, but with increasing altitude, maximum outflow became established over the northwest quadrant. Inflow and outflow became aligned across the circulation center and rotated anticyclonically, such that, by 4 km maximum inflow was located in the southwest quadrant and outflow covered the eastern half of the TC. Although Guillermo began rapid intensification with an asymmetric radial wind field on 02 August, the intensification resulted in an axisymmetric radial wind field on 03 August. Inflow values of 20 m s^{-1} surrounded the eyewall at 100 m altitude on 03 August. The depth of the inflow layer was reduced with decreasing radius from the circulation center. Outflow above the inflow layer increased in conjunction with the reduction of the inflow layer near the eyewall.

On 02 August temperatures at 100 m in the northeast inner core were 1.5-2 °C cooler when compared to the southwest inner core. On 03 August inner core temperatures were warmer and more uniform. Cooler temperatures were collocated with precipitation and support the presence of downdrafts on both days. The western half of the TC was more than 1.0 °C warmer than the eastern half at 1.5 km and may have been in response to subsidence. Temperatures in the eye below 2.5 km did not change from 02 August to 03 August. On both days outer core temperatures exhibited weak temperature gradients at 4 km.

Increases of θ_e within the inner core occurred at all levels on 03 August. At 1.5 km a 10 K increase was observed in the eye and eyewall region. A crescent shaped band of increased θ_e values was located in the lowest 1.5 km over much of the eastern outer core beyond 150 km from the TC center. The cause and role of such an increase far from

the inner core was intriguing and requires further analysis, especially since the increase occurred in the TC's wake where SST was likely cooler and wind speeds did not change much in this region on 03 August.

6.2 Discussion and Synthesis

Perhaps the most challenging questions raised from this dataset were: How did Guillermo manage to deepen at a rate of 2 hPa h^{-1} on 02 August with such an asymmetric structure and limited region of strong inflow beyond 75 km from the TC center? Why did Guillermo remain steady-state and cease rapid intensification on 03 August when it had yet to reach maximum potential intensity, was in a very similar synoptic environment as the previous day, and had a more complete eyewall with stronger and nearly symmetric inflow? The most intense convection, strongest low level inflow, and highest winds were all located over the eastern half of the TC on 02 August, yet despite the disparity, the TC deepened at a rate of 2 hPa h^{-1} . Perhaps Guillermo was using the asymmetric structures to its advantage during rapid intensification.

The negative vertical velocities from the 700 hPa aircraft, the lack of intense convection in the inner and outer cores at the start of the mission, as well as warmer temperatures over the western outer core at 1.5 km all support the existence of subsiding air. The thermodynamic profile of GPS sonde 140 (Fig. 39) indicated a stable atmosphere over the western inner core. Low level air over the western half of the TC was capped and continued to collect heat and moisture fluxes from the sea surface as it rotated cyclonically around the circulation center. Strong outflow at 1.5 km advected high θ_e away from the inner core. GPS sonde 16, contained a vertical profile of θ_e that increased with height (Fig. 40). Wroe and Barnes (2003) and Barnes and Powell (1995)

have shown that under certain conditions θ_e can increase above an inflow layer as a result of outflowing air. This process was discussed in detail for Hurricane Bonnie (1998) by Wroe and Barnes (2003). The result was a powerful combination; a stable insulating layer where θ_e steadily increased as the air rotates cyclonically around the TC.

Inflow at 100 m was weak over the western half of the TC, but steadily increased as air from the west rounded the southern portion of the TC. Once the air reached the focused channel of maximum inflow in the southeast quadrant it rapidly moved closer to the eyewall. Some of the high θ_e air likely reached the southeast eyewall and may have aided in the initiation of updrafts. Eastin et al. (2005a) examined the updraft cores at 5.5 km altitude on this day and found the 6 strongest updraft cores in the southeast quadrant. The thermodynamic profile about 100 km southeast of the circulation center was conditionally unstable and reveals a remarkable change from what was observed over the western half of the TC (Fig. 41). The high θ_e air allowed for robust convection to more successfully wrap around the eye and reduce the eye diameter quickly. These episodes of eye diameter reduction were in conjunction with pulses of immediate pressure decreases, thereby rapidly intensifying the TC. The stronger, axisymmetric inflow on 03 August reduced the amount of time air can undergo an increase of θ_e .

Traditionally, forecasters rely heavily on synoptic conditions when making intensity forecasts. Although synoptic conditions around Guillermo were favorable for intensification there was no robust signal that indicated rapid intensification was likely. GPS sonde data, radar reflectivity, and in-situ aircraft data indicate that the RI of Guillermo was in response to inner core processes. This study has documented the low-level thermodynamic, kinematic, and reflectivity fields during and subsequent to rapid

intensification. Analysis of these fields indicated that symmetric structures are not required for rapid intensification. In addition, asymmetric structures can persist even after rapid intensification concludes. The spiraling of eyewall convection into the eye was an effective process to reduce the eye diameter and triggered an immediate response of the inner core. Since convection was short-lived in the eye repeated attempts were required to maintain the deepening. High θ_e air, after having acquired energy over the west half of the TC, was injected into the southeast eyewall by an inflow maximum and aided in the maintenance of the intense east eyewall convection.

6.3 Future Work and Recommendations

Current TC intensity research is beginning to focus more on the mesoscale and is encouraged. Future missions investigating intensity, especially TCs undergoing rapid intensification, should concentrate sampling efforts within the inner core region of a TC. Guillermo's reflectivity and difference fields suggested that the configuration of eyewall convection can produce an immediate pressure decrease. It is vital to sample the tight gradients of the eyewall to understand the interaction of the eye and eyewall and the eyewall and adjoining rainbands. An inner core region, densely populated with GPS sondes, during an entire intensification period (~24 h) is highly advantageous to the research community because it would help answer the following questions: How does the distribution of θ_e in the low-level inner core evolve during intensification? Is the depth of the inflow layer a more important factor than the symmetry of the flow around the eyewall? What is the most effective process for reducing an eye diameter? Is the lowering of pressure episodic or more uniformly distributed during intensification?

Table. 1. Synoptic conditions, storm intensity, and motion. Data taken from “Best Track” and SHIPS predictor database (Kaplan and DeMaria, 2003).

Date and Time (UTC)	MSLP (hPa)	Vmax (m s ⁻¹)	Motion (degrees m s ⁻¹)		SST (°C)	200-850 hPa Shear (m s ⁻¹ degrees)		MPI (m s ⁻¹)
01 Aug 1200	990	31	275	5.0	29.6	3.1	320	86
02 Aug 0000	983	36	280	5.1	29.9	7.8	355	89
02 Aug 1200	969	46	275	5.3	29.9	6.1	015	89
03 Aug 0000	947	59	275	5.1	29.9	8.3	345	89
03 Aug 1200	925	69	275	5.3	29.8	8.4	005	88
04 Aug 0000	929	67	280	6.1	29.2	5.5	350	82
04 Aug 1200	925	69	275	6.5	28.9	7.4	010	80

Table. 2. GPS sonde pressure, temperature, humidity, and wind sensor specifications.

	Range	Accuracy	Resolution
Pressure	1080-100 hPa	± 1.0 hPa	0.1 hPa
Temperature	-90 to +60 C	± 0.2 C	0.1 C
Relative Humidity	0-100%	± 5%	1.0%
Horizontal Wind	0-200 m/s	± 0.5 m/s	0.1 m/s

Table 3. Recommended operational wind adjustment factors for extrapolating reconnaissance flight-level winds to the surface. [From Franklin et al. (2003).]

Flight level	Eyewall	Outer vortex (convection)	Outer vortex (not in convection)
700 hPa	0.90	0.85	0.80
850 hPa	0.80	0.80	0.75
925 hPa	0.75	0.75	0.75
1000 ft (305 m)	0.80	0.80	0.80

Figure 1. “Best Track” 1-minute sustained 10 m wind speed and surface pressure data for Guillermo. Two gray columns identify times when NOAA aircraft sampled the TC.

Figure. 2. Portion of Guillermo "Best Track". Obtained from <http://cimss.ssec.wisc.edu/tropic/archive/1997/storms/guillermo/guillermo.track.gif>.

Figure. 3. Storm-relative location of GPS sondes used in the analysis. Green (orange) dots indicate 02 August (03 August). The black circle indicates the TC center.

Figure. 4. Number of eyewall GPS sondes that reported winds, as a function of elevation for 17 hurricanes. [From Franklin et al. (2003).]

Figure 5. a) ASPEN processed temperature (red) and dewpoint (blue) profiles plotted on a Skew-T diagram. Dewpoint profile is saturated to surface and suffers from sensor wetting. b) Manually corrected dewpoint profile.

Figure 6. As is Fig. 5, but corrected for low dewpoint bias.

Figure 7. a) 100 m total wind speed field on 02 August without GPS sonde data in eye and eyewall. b) 100 m total wind speed field with extrapolated aircraft data and extension of GPS sonde winds in the eye from 400 m.

Figure 8. a) 240 km x 240 km lower fuselage plan view reflectivity image taken at 18:54.26 UTC on 02 August (pass 1) near 700 hPa. Plane indicated by cross at image center. b) at 00:03.44 UTC on 03 August (pass 10).

Figure 9. a) A 20 km x 120 km WNW – ESE vertical cross section reflectivity image taken in the eye at 23:33.55 UTC on 02 August near 700 hPa. Small cross in lower center portion of image represents the location of the plane. Reflectivity values in the eye at the surface depict the sea surface and not precipitation. b) A WSW – ENE vertical cross section taken in the eye at 00:02.59 UTC on 03 August.

Figure 10. North-south and east-west measurements of eye diameter and their mean on 02 August.

Figure 11. a) As in Fig. 8, but taken at 20:42.06 UTC on 02 August (pass 4). b) at 21:19.05 UTC on 02 August (pass 5). c) at 21:54.11 UTC on 02 August (pass 6).

Figure 12. a) As in Figure 9, but a WSW – ENE cross section taken in the eye at 21:22.03 UTC on 02 August. b) a WSW – ENE cross section taken in the eye at 21:23.03 UTC on 02 August.

Figure 13. Flight-level temperature, corrected dewpoint, and wind speed measurements from the 700 hPa aircraft as it departs the eye of Guillermo during the 5th pass through the center. The arrow represents the direction of the aircraft and the distance from the eye center is displayed along the x-axis. The gray bar indicates the period when the aircraft encounters the spiraling band entering the eye.

Figure 14. a) As in Fig. 8, but taken at 19:11.49 UTC on 03 August (pass 1). b) at 00:24.06 UTC on 04 August (pass10).

Figure 15. a) As in Figure 9, but a W – E cross section taken in the eye at 19:47.02 UTC on 03 August. b) a WNW – ESE vertical cross section reflectivity image taken in the eye at 22:33.02 UTC on 03 August

Figure 16. Mean eyewall echo tops for 02 August (green line) and 03 August (orange line). ENE and WSW azimuths not sampled on 03 August

Figure 17. Net LHR calculations for each pass through the eye on 02 August (blue line) and 03 August (orange line). Reflectivity images used in the analysis are included. These images are centered on the aircraft when in the eye and go out 60 km.

Figure 18. a) Storm centered composite total wind field (m s^{-1}) on 02 August at 100 m. Location of GPS sondes indicated by black identification numbers. Numbers that begin with 999 are extrapolated data. Black ring indicates the 75 km radius from the circulation center that divides the inner and outer cores. b) at 1.5 km. c) at 4.0 km.

Figure 20. a) Total wind (m s^{-1}) difference field (03 August – 02 August) at 100 m. Distance from circulation is displayed in km along the x- and y-axis. White circle in image center intentionally covers the 25 km radius from the circulation center. The black ring represents the 75 km radius from the circulation center. b) at 1.5 km. c) at 4 km.

Figure 21. Total wind speed measurements from the 700 hPa aircraft flying corresponding NNE – SSW eye passes at 700 hPa. 02 August (03 August) is represented by the green (orange) line.

Figure 22. As in Fig. 18, but for tangential wind.

Figure 23. As in Fig. 18, but for tangential wind on 03 August.

Figure 24. As in Fig. 20, but for tangential wind.

Figure 25. As in Fig. 18, but for radial wind.

Figure 26. As in Fig. 8, but taken at 19:12.26 UTC on 02 August.

Figure 27. Height-azimuth cross section of radial wind on 02 August 100 km from the circulation center. Inflow (outflow) values are negative (positive).

Figure 28. As in Fig. 18, but for radial wind on 03 August.

Figure 29. As in Fig. 27, but for 03 August.

Figure 30. As in Fig. 27, but at 55 km from the circulation center on 03 August.

Figure 31. Vertical radial wind profiles obtained from four GPS sondes along a straight azimuth north of the TC towards the eye center (0.0 km). The distance from the profile to the eye is located on top of each profile. The zero line is marked by a dotted line. Inflow (outflow) values are negative (positive).

Figure 32. As in Fig. 18, but for temperature (°C).

Figure 33. As in Fig. 18, but for temperature ($^{\circ}\text{C}$) on 03 August.

Figure 34. As in Fig. 20, but for temperature.

Figure 35. Average eye temperature profiles from 02 August (green) and 03 August (orange). The 02 August (03 August) lapse rate is an average of 2 (5) temperature profiles from GPS sondes released near 500 hPa.

Figure 36. As in Fig. 18, but for equivalent potential temperature (K).

Figure 37. As in Fig. 18, but for equivalent potential temperature (K) on 03 August.

Figure 38. As in Fig. 20, but for equivalent potential temperature (K).

Figure 39. Temperature (red) and dewpoint (blue) profiles plotted on a Skew-T diagram for GPS sonde 140 deployed at 21:04 UTC near 500 hPa on 02 August.

Figure 40. a) Vertical profile of radial wind for GPS sonde 16 deployed at 19:50 UTC from near 500 hPa on 02 August. b) for θ_e .

Figure 41. As in Fig. 39, but for GPS sonde 1402 deployed at 22:05 UTC.

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