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Effects of Environmental Water Vapor on Tropical Cyclone Structure and Intensity

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EFFECTS OF ENVIRONMENTAL WATER VAPOR ON TROPICAL CYCLONE STRUCTURE AND INTENSITY

By

Derek Ortt

A THESIS

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of the University of Miami
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EFFECTS OF ENVIRONMENTAL WATER VAPOR ON TROPICAL CYCLONE
STRUCTURE AND INTENSITY

Derek Ortt

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The tropical cyclone (TC) and environmental interaction is not fully understood. Previous studies have demonstrated that this interaction affects intensity change. The studies found that intensification is favored in low shear, moist environments, with high sea surface temperatures (SST). However, little precise quantification was provided, especially in terms of the impact of environmental water vapor on TC intensity change. This work addresses the TC interaction with the environmental water vapor. Results from a comprehensive statistical study show that TC intensification is more likely to occur in an anomalously moist environment than a dry environment. However, only a small amount of the total variance is explained. When assessing the effect of vertical wind shear along with environmental water vapor, more of the variance is explained.

Water vapor not only affects TC intensity. Prior modeling studies have demonstrated impacts from environmental water vapor on TC structure. These impacts can also affect intensity change. Specifically, enhanced water vapor content within the TC enhances the rainbands, which can lead to an eyewall replacement cycle, causing a temporary weakening, followed by re-intensification. This thesis evaluates observational and high resolution MM5 model output from Hurricanes Katrina and Rita from the Hurricane Rainband and Intensity Experiment (RAINEX) to evaluate the effects of varying water vapor distributions on TC structure. While the two hurricanes were of
similar intensity, they had different water vapor distributions and structures. Rita underwent an eyewall replacement cycle while under RAINEX surveillance while Katrina did not. Rita was also located within a dry environment and had a strong horizontal moisture gradient, while Katrina was in a moist environment and had a weak moisture gradient. Results suggest that a strong horizontal water vapor gradient, with a moist TC and dry outer environment may confine the hurricanes into a pattern that causes them to have high circularity, promoting the formation of a secondary eyewall. The dry outer environment had strong atmospheric stability and was less favorable for deep convection far from the center in the Rita case. The moist environment in the Katrina case was more unstable. This may have allowed for the rainbands to be farther from the center in a less circular pattern than Rita. The results presented in this thesis suggest that this pattern is less favorable for an eyewall replacement cycle.
I dedicate this thesis to the Lord, Jesus Christ.
Without Him giving me the ability, this thesis would not be possible.
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I also thank those who provided me with the data. Specifically, Remote Sensing Systems for all microwave water vapor data, the Hurricane Research Division of the National Oceanic and Atmospheric Administration for providing all in situ measurements from the G-IV and NOAA P3 aircraft, and the Hurricane Rainband and Intensity Experiment for providing the in-situ measurements from the NRL P3 aircraft, along with the high resolution model output.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>List</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiii</td>
</tr>
<tr>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Review of internal and environmental factors affecting TC structure and intensity change</td>
<td>2</td>
</tr>
<tr>
<td>1.2.1 Environment/TC Interactions</td>
<td>2</td>
</tr>
<tr>
<td>1.2.2 TC internal dynamics, and rainband-eyewall interaction</td>
<td>5</td>
</tr>
<tr>
<td>1.3 Science Objectives</td>
<td>7</td>
</tr>
<tr>
<td>2 DATA AND MODEL DESCRIPTIONS</td>
<td>8</td>
</tr>
<tr>
<td>2.1 Observational datasets</td>
<td>8</td>
</tr>
<tr>
<td>2.1.1 Total precipitable water and rainrate</td>
<td>8</td>
</tr>
<tr>
<td>2.1.2 Vertical wind shear</td>
<td>11</td>
</tr>
<tr>
<td>2.1.3 GPS dropsondes</td>
<td>13</td>
</tr>
<tr>
<td>2.2 High-resolution model forecast fields</td>
<td>15</td>
</tr>
<tr>
<td>3 ENVIRONMENTAL WATER VAPOR AND TC INTENSITY CHANGE</td>
<td>18</td>
</tr>
<tr>
<td>3.1 Environmental water vapor distribution in the tropical Atlantic</td>
<td>18</td>
</tr>
<tr>
<td>3.2 Statistical relationship of water vapor and intensity change</td>
<td>19</td>
</tr>
<tr>
<td>3.3 Combined effects of water vapor and vertical wind shear</td>
<td>26</td>
</tr>
<tr>
<td>3.4 Summary</td>
<td>31</td>
</tr>
<tr>
<td>4 EFFECTS OF WATER VAPOR ON RAINBANDS</td>
<td>33</td>
</tr>
<tr>
<td>4.1 Hurricane rainband and intensity change experiment (RAINEX)</td>
<td>33</td>
</tr>
<tr>
<td>4.2 Hurricanes Katrina and Rita</td>
<td>34</td>
</tr>
<tr>
<td>4.3 Environmental water vapor distributions for Katrina and Rita</td>
<td>38</td>
</tr>
<tr>
<td>4.3.1 Outer environment</td>
<td>38</td>
</tr>
<tr>
<td>4.3.2 Water vapor in between rainbands</td>
<td>44</td>
</tr>
<tr>
<td>4.3.3 Evolution of water vapor distribution</td>
<td>45</td>
</tr>
<tr>
<td>4.4 Rainband structures</td>
<td>46</td>
</tr>
<tr>
<td>4.4.1 Circularity of rainbands around the storm</td>
<td>46</td>
</tr>
<tr>
<td>4.4.2 Moist stability index and rainband development</td>
<td>61</td>
</tr>
<tr>
<td>4.5 Development of moat regions</td>
<td>67</td>
</tr>
<tr>
<td>4.6 Summary</td>
<td>76</td>
</tr>
</tbody>
</table>
List of Figures

2.1 Sample model domains used for the MM5 Katrina and Rita Forecasts. Outer domain is fixed, while inner-two domains follow the vortex. For the forecasts, the domains were shifted to the west due to the location of Katrina and Rita................................................................. 17

3.1 Climatological TPW in mm for the Atlantic Basin during the hurricane season calculated from the average of SSM/I data of June-October from 1988-2005. Magenta dots represent the locations of TCs with NOAA G-IV flights during the hurricane seasons from 1997-2005....................... 18

3.2 Comparison mean TPW from 1987-2005 for tropical storms (white), category 1-2 hurricanes (gray), and category 3-5 hurricanes (black), along with the comparison of the mean of intensifying (group A), steady (group B), and weakening (group C) cyclones within each group........... 21

3.3 Scatterplots and probability distributions of water vapor and corresponding intensity change for (a) tropical storms, (b) category 1-2 hurricanes, and (c), category 3-5 hurricanes. Vertical black lines represent mean TPW for each group. Includes all storms from 1987-2005. Contours labels denote the probability contours....................... 22

3.4 Composite mean RH TC soundings from the surface to 11km from 1998-2005. Tropical storms are denoted by the red line, category 1-2 hurricanes by the black, category 3-5 hurricanes by the blue, and the Jordan mean sounding from the West Indies for the months of July
3.5 Composite mean relative humidity profile from the GPS dropsondes from 1998-2005 for intensifying, steady, and weakening TCs.

3.6 Probability distributions of vertical wind shear and corresponding intensity change for tropical storms (a), category 1-2 hurricanes (b), and category 3-5 hurricanes (c). Vertical line represents mean shear for each group. Time period is from 1987-2005. Contour labels denote the probability contours.

3.7 Probability distributions of favorability points vs. 12-hour intensity change for tropical storms (a), category 1-2 hurricanes (b), and category 3-5 hurricanes (c). Time period is from 1987-2005. Contour labels denote the probability contours.

3.8 Four storm centered SSM/I passes of Hurricane Georges from 2230 Sept 18 (a), 1106 Sept 19 (b), 0027 Sept 20 (c) and 1240 Sept 20 (d). The contouring for the plots is every 10mm. The SHIPS vertical wind shear in m s\(^{-1}\) is in panel (e) and the best track intensity in hPa is in panel (f). The black dots represent in panels (e) and (f) correspond to the times of the SSM/I passes. Dot a corresponds to the pass in panel (a), dot b to panel (b), dot c to panel (c) and dot d to panel (d).

4.1 MM5 and Best track for Hurricanes Katrina (a) and Rita (b). Black (red) dots are the best track (MM5) positions every 6 (1) hours.

4.2 MM5 and best track intensity of Hurricanes Katrina (a) and Rita (b).

4.3 TMI TPW for Hurricane Katrina from 2048 UTC August 27 (a), 0330
4.4 TMI TPW for Hurricane Rita from 0806 UTC September 22 (a), and 1448 UTC September 22, 2005 (b)……………………………………………………………

4.5 Daily composite of the G-IV dropsonde profiles in the outer environment (250-600km) of Hurricanes Katrina on 27 August (cyan) and 28 August (blue) and Rita on 21 September (magenta) and 22 September (red). The profile in black is the mean for category 3-5 hurricanes from 1997-2005 mean sounding from Chapter 3………………

4.6 Same as in Fig. 4.5 expect from the MM5 output……………………………………

4.7 Composite RH vertical profiles from the rainband regions (defined as area between convective rainbands located outside of the radius of hurricane force winds) for Hurricanes Katrina and Rita from the P3 dropsondes (a) and MM5 (b). The color scheme is the same as used in Fig. 4.5……………………………………………………………………

4.8 Azimuthally averaged MM5 RH at 600 hPa level for (a) Hurricanes Katrina from 0000 UTC 27 August-1200 UTC 29 August and (b) Rita from 1200 UTC 21 September-12 UTC 23 September…………………

4.9 TRMM TMI rainrate (mm/h) of Katrina from 0325 (a) 2130 UTC August 28, 2005 (b) and rainband circularity of Katrina (c and d) from the times of the rainrate images (a and b). Black line represents secondary eyewall candidate threshold of .50……………………………………

4.10 Flight level data from NOAA 43 for Hurricane Katrina. Blue represents flight level winds (kts), black represents SFMR surface winds (kts),
while the green and dashed red lines represent the temperature and
dewpoint (K)…………………………………………………………………………………. 50

4.11 Same as Fig 4.9 except for the MM5 output at 2100 UTC August 28,
2005……………………………………………………………………………………….. 52

4.12 Time radius diagram of rainband circularity for Hurricane Katrina from
MM5 output from 0000 UTC August 27 to 1200 UTC August 29, 2005.. 53

4.13 Time-radius diagram of the azimuthal average of the common log of the
potential vorticity scaled by a factor of 30 (PV) for Hurricane Katrina
from MM5 output. Times are the same as in Fig 4.12…………………. 53

4.14 TMI rainrate images (mm/h) of Hurricane Rita from 0812 UTC
September 22 (a) and 1348 UTC September 23 (b), 2005 along with
rainband circularity (c and d) from the times of the rainrate images.
Black line represents .50 circularity secondary eyewall threshold……….. 57

4.15 700mb Air Force Flight level data for Hurricane Rita on September 22,
2005 from 0650-0740 UTC (a), 1050-1140 UTC (b), 1850-1940 UTC
(c) and 2310 to 0000 UTC September 23 (d). Blue represents flight level
winds (KT), while the green and dashed red lines represent the
temperature and dewpoint (K)…………………………………………………………….. 58

4.16 Same as Fig 4.14, except for MM5 output from 1100 UTC September
22……………………………………………………………………………………………. 59

4.17 Time-radius diagram of rainband circularity from MM5 output for
Hurricane Rita from 1200 UTC September 20, 2005 to 1200 UTC
September 23, 2005………………………………………………………………………… 60
4.18  WSR-88D radar reflectivity (DBZ) from Lake Charles, Louisiana of Hurricane Rita from 0005 UTC, September 24, 2005

4.19  Azimuthally averaged scaled PV from MM5 output for Hurricane Rita from 1200 UTC September 20, 2005 to 1200 UTC September 23, 2005.

4.20  Daily composite mean theta-e/theta-e* profiles from GPS dropsondes for Hurricanes Katrina on August 27 (a) and 28 (b) and Rita on September 21 (c) and 22 (d) Vertical line represents theta-e at surface.

4.21  Same as Fig 4.20 except for the MM5 forecasts.

4.22  Observed (black) and MM5 (red) daily composite mean MSI of Hurricanes Katrina (left) and Rita (right) within the outer storm environment. Observed mean was derived from GPS dropsondes.

4.23  Azimuthally averaged MM5 MSI Hurricanes Katrina (a) from 0000 UTC August 27 to 0000 UTC August 30 and Rita (b) from 1200 UTC September 21 to 1200 UTC September 23. The white contour represents the Jordan Mean Sounding MSI of 2.5K.

4.24  Azimuthally averaged MM5 rain rate overlaid with 2.5K (white) and 10K (magenta) MSI contours of Hurricanes Katrina (a) and Rita (b). The times are the same as in Fig 4.23.

4.25  Skew-T diagram from an NRL dropsonde deployed in the moat of Hurricane Rita at 1801 UTC, September 22, 2005. Red line is the temperature and blue line is the dewpoint.

4.26  Skew-T diagrams of Hurricanes Katrina (a and b) and Rita (c and d) from the MM5 output at 0800 UTC August 28, 2005 for Katrina and
1100 UTC September 22 for Rita. The red line is the temperature and the blue line is the dewpoint. The soundings were taken from the moat of Rita and from the moat like area of Katrina.

4.27 MM5 dBZ and radial/vertical wind cross sections of Hurricane Rita from September 22, 2005 at 0000 UTC (a), 0600 UTC (b), 1100 UTC (c), and 2100 UTC (d).

4.28 Same as Fig 4.27, except for Hurricane Katrina on August 28, 2005 at 0000 UTC (a), 0600 UTC (b), 1200 UTC (c), and 1900 UTC (d).

5.1 Conceptual model of moisture gradient and TC rainband structures. Relatively weak gradient (left) may favor for extended spiraling rainbands as in the case of Katrina, whereas a strong moisture gradient may be a factor that confining the rainbands at the radius where the strong gradient is. Areas inside of the red circle represent very moist and unstable environment while areas outside of the light blue represent dry and stable. The teal shapes represent the TC rainbands.

5.2 TRMM TMI water vapor image (a) and 85 GHz (b) for Hurricane Frances from 1021 UTC, August 30, 2004.

5.3 Composite environmental RH profile from G-IV dropsondes for Hurricane Katrina from August 26, 2005.
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Number of SSM/I TPW observations used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>TMI passes available of Katrina and Rita. Passes are those from the category 3-5 stage</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>Number of SHIPS 200-850 hPa shear observations used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes</td>
<td>12</td>
</tr>
<tr>
<td>2.4</td>
<td>Coefficients applied to the favorability index, derived from multiple linear regression. Coefficients shown here are normalized by the maximum co-efficient</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>Number of G-IV flights (dropsondes) used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>Number of RAINEX P3 and G-IV dropsondes used in the Katrina and Rita case study. P3 dropsondes were deployed between the rainbands while G-IV sondes were deployed in the outer storm environment</td>
<td>15</td>
</tr>
</tbody>
</table>
3.1 Definitions of intensifying, steady, and weakening TCs for tropical storms, category 1-2 hurricanes, and category 3-5 hurricanes. Values in table represent change in MSLP for the 12 hours after the data observation.

4.1 Mean TPW in mm from the outer storm environments (250-600km) for Hurricanes Katrina and Rita. Only the times where the outer environment has at least 50 percent data coverage are included.
Chapter 1: Introduction

1.1 Motivation

Forecasting intensity changes in tropical cyclones (TC) has long been an unresolved issue for researchers and forecasters alike. This fact has been highlighted in recent years as many TCs made landfall along the US coasts have experienced unexpected rapid intensity changes, some in the hours immediately before landfall. Hurricanes, Charley, Katrina, Rita, and Wilma in 2005 clearly demonstrate the need to better understand the factors that cause rapid intensification. Wilma in a six hour period intensified from a category 1 hurricane with winds of 38 m s$^{-1}$ to a category 4 hurricane with winds of 67 m s$^{-1}$, and set the record for the most intense TC ever observed in the western hemisphere a mere three hours later (Pasch et al., 2006). In 2004, Hurricane Charley underwent rapid intensification from 46 to 67 m s$^{-1}$ in the eight hours before landfall (Pasch et al., 2005). In contrast, Hurricanes Lili in 2002 (Lawrence, 2003) and Dennis in 2005 (Beven, 2006) underwent rapid weakening in the hours before landfall. These rapid intensity changes were not well captured by the current operational forecast models and official forecasts from the National Hurricane Center. While part of the forecasting error is due to limitations in the relatively low-resolution numerical weather prediction models, some is due to a lack of understanding of TC internal dynamic processes and TC interaction with the large-scale environment, both in the atmosphere and ocean.

One of the difficulties of addressing the questions related to TC-environmental interaction is the lack of observations over the open ocean. Satellite data provides
valuable global coverage. However, a full three-dimensional description of the atmosphere remains unavailable due to the lack of temporal and spatial resolution, especially the limitation in observing vertical structure of the atmosphere in satellite observations. The airborne GPS dropwindsonde data from the G-IV aircraft in hurricanes have provided the badly needed vertical profiles of temperature, water vapor, and wind in the hurricane environment since 1997. Recent field programs, such as the Hurricane Rainband and Intensity Change Experiment (RAINEX), have provided multi-aircraft radar and dropsonde data inside of hurricanes. This study will take advantage of these comprehensive data sets to address the effects of the environmental water vapor distribution and variability on the TC structure and intensity change.

1.2 Review of Environmental and Internal Factors Affecting TC Structure and Intensity Change

1.2.1 Environment-TC Interactions

Research has been conducted during the last 60 years to address the issue regarding the environmental and internal impacts on TC intensity and structure. Until the last several years, the research generally focused on the environmental factors. Early research centered on the sea surface temperature (SST). Riehl (1948) stated that a hurricane is largely driven by the evaporation of water from the sea. Later work, including Ramage (1959) and Gray (1968) confirmed and expanded upon this. These works concluded that TC genesis and intensification requires SST >26.5°C. Later, upper tropospheric temperatures were found to have a significant impact on TC intensity.
Emanuel (1986) and DeMaria and Kaplan (1999) found cold upper tropospheric temperatures decrease static stability, allowing for greater TC intensification.

Vertical wind shear is another significant contributor to TC intensity change and has been studied extensively. Gray (1968) proposed that strong vertical wind shear advects heat and moisture away from the vortex, preventing concentrated tropospheric heating and intensification. DeMaria (1996), proposed a different mechanism for vertical shear to prevent TC intensification. Based upon results from Jones (1995), DeMaria (1996) showed vertical wind shear causes a vertical tilt of potential vorticity (PV). It was shown that this tilt creates a warm temperature anomaly aloft up-shear and over the vortex, stabilizing the atmosphere. This results in an asymmetric storm as only the downshear portion can sustain deep convection, often leading to weakening. Related to the topic of vertical shear is upper tropospheric trough interaction. This can cause an increase in the vertical shear and result in weakening, or it can aid in the intensification if the outflow is enhanced or if potential vorticity is advected over the TC (Hanley et al., 2001). Vertical wind shear also affects TC structure. Strong vertical shear creates asymmetries in the convection, with the rainfall largely displaced down-shear left of the shear vector (Black et al., 2002, Rogers et al., 2003, Chen et al. 2006). Chen et al. (2006) found that the TC rainfall asymmetry increases as storm intensity and vertical shear increases. The largest asymmetries are found in category 3-5 hurricanes with vertical shear greater than 7.5 m s⁻¹. Chen et al. (2006) also found that storm forward motion becomes an important factor affecting the rainfall asymmetry when the wind shear is weaker than 5 m s⁻¹. Thus, vertical shear causes TC structural changes, along with intensity changes.
Atmospheric water vapor is another factor important for TC intensification. Gray (1968) argued that it is the condensation of water vapor in the atmosphere that is critical to a developing TC, though there was little precise quantification. Recent studies have examined and quantified the impacts of water vapor on TC intensity and genesis in more detail. Pennington (2003) documented that tropical cyclogenesis was more frequent in regions of above average total precipitable water (TPW). Kimball (2006) through numerical modeling simulations of Hurricane Ivan near landfall was able to demonstrate the impacts of water vapor on fully developed TCs. Dry air intrusions tended to cause downdrafts. The downdrafts weakened the deep convection, which is well documented to be critical to TC intensification (e.g. Gray, 1967 and Gray, 1968). The Kimball results are not restricted to TCs near landfall. Observational results from Gray et al. (1975) and Zuidema et al. (2006) and modeling results from Tompkins (2001) demonstrate that areas of deep convection are associated with regions of enhanced water vapor content and clear areas tend to be drier; thus, the Kimball conclusions can be applied beyond Hurricane Ivan.

Despite the progress previously stated, much remains unknown about TC and environmental interaction. This is especially true when there are varying environmental water vapor distributions. Interactions between a storm and environmental dry air can be quite complex. Hurricane Georges in 1998 was a classic example. Although the environment was relatively dry, Georges intensified to a strong Cat 4 hurricane in the east of the Leeward Islands. (Guiney 1999, Cangialosi and Chen 2006). In the 12 hours before landfall, the dry air intruded into Georges’ inner core at a time when the wind shear increased (to be shown in chapter 3). At this time, the hurricane weakened rapidly from
69 to 51 m s\(^{-1}\) (Guiney, 1999) in a 12 hour period. This demonstrates the importance of understanding precisely how water vapor affects intensity change.

### 1.2.2 TC internal dynamics, and rainband-eyewall interaction

TC interaction with the large scale environment is only one factor affecting intensity change. Another is the TC internal dynamics, specifically eyewall replacement cycles. Willoughby et al. (1982), Willoughby (1990), and Black and Willoughby (1992) documented periods of significant intensification and weakening in Atlantic category 3-5 hurricanes (including Allen, 1980 and Gilbert, 1988) during eyewall replacement cycles. The reason for the intensity changes during these cycles can be attributed to changes in the storm radius of maximum wind (RMW). Willoughby (1990) showed through a convective ring model (Shapiro and Willoughby, 1982) that as the (RMW) contracts, a TC intensifies and as it expands, the storm weakens. During eyewall replacement, the primary eyewall initially contracts, and the TC intensifies. As the rainbands form into an outer eyewall, the primary eyewall dissipates, shifting the RMW to the outer eyewall, causing weakening. (Willoughby et al., 1982).

Recent modeling studies of Montgomery and Kallenbach (1997), Schubert et al. (1999), Kossin et al 2000, Chen and Yao (2001), Wang (2002), and the observational study by Corbosiero et al. 2006 began to assess the rainband and eyewall interaction and how this could lead to secondary eyewall formation. Specifically, the studies theorized that vortex Rossby Waves (VRW), waves of potential vorticity (PV) propagating out from the eyewall due to the strong radial gradient of potential vorticity, are critical to rainband and secondary eyewall formation. These waves then propagate outward from
the center until the PV gradient weakens or changes sign due to a ring of enhanced PV associated with a secondary eyewall (Kossin et al. 2000). However, these studies suffered from two setbacks. The modeling studies, except for Wang (2002) used an idealized model with dry dynamics, which was unable to account for the generation of PV through diabatic heating from moist convection (McIntyre, 1993, May and Holland, 1999). The second drawback is that the interaction with the large scale environment was not considered in any of the studies. Few studies addressed the outer rainbands, which may be subject to environmental influence. Instead, most studies focused on the inner-rainbands. Thus, no conclusions regarding how the large scale environment interacts with and affects the internal processes could be drawn.

A small number of studies have addressed the impact of the large scale water vapor distribution on secondary eyewall formation. Emanuel (1995), Nong and Emanuel (2003), and Lonfat (2004) have demonstrated that TCs with high quantities of water vapor have enhanced convective rainbands that can lead to a secondary eyewall formation. Enhanced rainbands have a negative impact on the inner-core due to the convective downdrafts, which transport low theta-e to the surface (Powell, 1990b). Furthermore, a concentric rainband about the eyewall reduces the amount of inflow into the eyewall, (Samsury and Zisper, 1995) and reduces its theta-e (Powell, 1990b). These two processes disrupt the eyewall and cause a temporary weakening (Willoughby et al., 1982). These studies show that the outer environment does influence the inner-core TC processes and should not be discounted.
1.3 Science Objectives

This study will focus on how the large-scale water vapor distribution affects TC structure and intensity change. A two step approach will be used. The first will focus on quantifying a statistical relationship between the environmental water vapor and TC intensity change over the Atlantic Ocean using both satellite and in situ dropsonde data. The second will address how the environmental water vapor affects the TC structure and evolution using the RAINEX observations from Hurricanes Katrina and Rita (2005). Specifically, the following questions will be addressed:

- Statistically, to what extent is environmental water vapor and TC intensity change correlated?
- Through what physical mechanism(s) can environmental water vapor affect TC structure and evolution? Does the water vapor interact with TCs through the outer rainbands?
- How do the outer rainbands interact with the TC inner core?
- Can variations in rainband structure due to different large-scale water vapor distributions lead to TC intensity change?
Chapter 2: Data and Model Descriptions

In this study we use the satellite observed vertically integrated precipitable water to describe both large-scale mean and variability surrounding TCs. In addition, the airborne GPS dropsonde data are used to provide a detailed vertical distribution. Based on the observational and modeling evidence that vertical wind shear often work in concert with the water vapor field influencing TC structure and evolution, we use the vertical shear data to provide additional analysis to examine the combined effects of the shear and moisture on TCs. To further examine the physical mechanism(s) that may play a role in TC structure and intensity change due to variations in water vapor, we use the RAINEX observations and high-resolution model forecast fields in Hurricanes Katrina and Rita in 2005.

2.1 Observational Data Sets

2.1.1 Total Precipitable Water and Rainrate

The NASA Special Sensor Microwave/Imager (SSM/I) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) derived total precipitable water (TPW) are used in both monthly averages and individual swaths. The SSM/I dataset used for this study spans from July 1987 through January 2006. Different years had different numbers of SSM/I satellites available, with 1987-1990 having one, 1991-1994 having two, with 1995-present having 3, except for 1997, which had four.

The monthly mean and individual SSM/I and TMI pass TPW data has a horizontal resolution of .25 degree and a twice daily temporal resolution. The SSM/I swath width is 1394km with TMI swath width of 759km. The SSM/I swaths are north/south, while the TMI are NE to SW and SE to NE. Between the swaths there is no
data and TPW data cannot currently be retrieved over land. Passes were excluded when there was less than 65 percent of data coverage from 200-600km from the center location, which was derived using a linear interpolation from the two nearest best track times to the time of the SSM/I or TMI pass.

The monthly mean SSM/I TPW was used to derive the climatological water vapor distribution for the tropical Atlantic during the hurricane season, as defined as June through October. Since SSM/I data is available from July 1987, 1987 was excluded; thus, the climatology consists of 1988-2005. The climatology was derived by calculating the mean TPW from the monthly TPW from 1988-2005 during the months of the hurricane season.

The daily SSM/I pass data was used to derive the statistical relationship between TPW and TC intensity change. Specifically, the mean TPW from the 200-600km annulus was correlated with the 12 hour minimum central pressure change as reported by the National Hurricane Center's best track database (Jarvinen et al., 1988). This was done for all TCs at tropical storm intensity (18 m/s) or greater that were located between the equator and 35N in the Atlantic Basin. The TCs were stratified into three intensity groups: tropical storms, category 1-2 hurricanes, and category 3-5 hurricanes, with the groups further divided into intensifying, steady-state, and weakening. Intensifying (weakening) TCs were defined as having a 12 hour pressure fall (rise) of 3 hPa for tropical storms, 5 for category 1-2 hurricanes, and 6 for category 3-5 hurricanes. These values are equivalent to ½ standard deviation of the intensity change for the three groups. The mean TPW content was then calculated for each of the three intensity groups, as well as for the intensifying, steady, and weakening TCs within each group to determine a
qualitative relation between TPW and intensity and intensity change. In addition, the mean TPW was correlated with the 12 hour intensity change to determine the quantifiable statistical relationship between TPW and intensity change. TCs were excluded from the dataset in landfall occurred within 6 hours of the SSM/I pass. TCs that made landfall between 6 and 12 hours were included and the intensity change from the time of the pass until landfall was considered to be its 12 hour intensity change. Table 2.1 lists the number of SSM/I TPW passes used.

<table>
<thead>
<tr>
<th></th>
<th>Intensifying</th>
<th>Steady</th>
<th>Weakening</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Storms</td>
<td>224</td>
<td>320</td>
<td>104</td>
<td>648</td>
</tr>
<tr>
<td>Cat 1-2 Hurricanes</td>
<td>117</td>
<td>165</td>
<td>63</td>
<td>345</td>
</tr>
<tr>
<td>Cat 3-5 Hurricanes</td>
<td>32</td>
<td>75</td>
<td>42</td>
<td>149</td>
</tr>
</tbody>
</table>

Table 2.1: Number of SSM/I TPW observations used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes.

The TRMM TMI TPW data was not used as a part of the statistical study. This was done to avoid any differences that may arise from the different instances. Instead, it was used exclusively to detect the large scale environmental water vapor distributions of Hurricane Katrina and Rita and how this interacted with the rainbands to affect the intensity of the two hurricanes, providing a physical mechanism through which environmental water vapor can affect TC intensity change. A slightly less restrictive 50 percent data coverage threshold was used for the TMI TPW as the 65 percent threshold
eliminated most of the data. In addition, the TMI surface rainrate estimates are used to analyze the rainband structure in the two hurricanes. Table 2.2 provides the dates and times that the TRMM TMI data is available for Hurricanes Katrina and Rita.

<table>
<thead>
<tr>
<th></th>
<th>Katrina</th>
<th>Rita</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/27</td>
<td>2048 UTC</td>
<td>9/21 0900 UTC</td>
</tr>
<tr>
<td>8/28</td>
<td>0330 UTC</td>
<td>9/21 1548 UTC</td>
</tr>
<tr>
<td>8/28</td>
<td>2130 UTC</td>
<td>9/22 0806 UTC</td>
</tr>
<tr>
<td>9/22</td>
<td>1448 UTC</td>
<td>9/22 1448 UTC</td>
</tr>
<tr>
<td>9/23</td>
<td>1348 UTC</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2: TMI passes available of Katrina and Rita. Passes are those from the category 3-5 stage.

TMI rainrate data has a horizontal resolution of 5km. The rainrate data was used exclusively for the evaluation of Hurricanes Katrina and Rita. Specifically, the rainrate data was used to assess the rainband circularity, which is defined for the purposes of this study as the fraction of coverage at a given radius of rainrate greater than 12.5 mm/h.

2.1.2 Vertical Wind Shear

Previous studies (e.g. Gray 1968, DeMaria 1996) have shown that vertical wind shear has a significant impact on TC intensity change. However, it has not been addressed extensively in the context of the combined impact of vertical shear and the water vapor distribution. This study addresses this topic to further explain how the water vapor distribution affects TC intensity change.

The vertical wind shear data used for this study is from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria and Kaplan 1994 and 1999) from the
years of 1987-2005. The wind shear data is available every six hours. The shear is calculated between the 200 and 850 hPa levels and in a 200-800km annulus from the center. Before quantifying the combined effects of wind shear and TPW, the effects of wind shear on intensity change were statistically quantified. The same analysis techniques that were used for the SSM/I TPW were used for the SHIPS shear, along with the same restrictions on data usage. Table 2.3 provides the number of cases used for the study.

<table>
<thead>
<tr>
<th></th>
<th>Intensifying</th>
<th>Steady</th>
<th>Weakening</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Storms</td>
<td>837</td>
<td>932</td>
<td>288</td>
<td>2057</td>
</tr>
<tr>
<td>Cat 1-2 Hurricanes</td>
<td>375</td>
<td>573</td>
<td>150</td>
<td>1021</td>
</tr>
<tr>
<td>Cat 3-5 Hurricanes</td>
<td>120</td>
<td>242</td>
<td>146</td>
<td>508</td>
</tr>
</tbody>
</table>

Table 2.3: Number of SHIPS 200-850 hPa shear observations used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes.

The combined effects of TPW and wind shear were then quantified. To quantify these effects, we define a weighted favorability index. The weighting is a function of the standard deviations above and below the mean of the shear and TPW. The index is defined as follows:

\[
FI = A\left[\frac{(TPW - \overline{TPW})}{\sigma_{TPW}}\right] - B\left[\frac{(S - \overline{S})}{\sigma_{s}}\right] \tag{2.1}
\]
where \( \sigma \) is the standard deviation, \( TPW \) is total precipitable water, \( S \) is the vertical shear from SHIPS, the overbar denotes the composite mean from 1987-2005, while A and B are weighting coefficients that are derived using multiple linear regression for each of the three groups. Table 2.4 lists the values of the coefficients.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Storms</td>
<td>.0937</td>
<td>1</td>
</tr>
<tr>
<td>Cat 1-2 Hurricanes</td>
<td>.3562</td>
<td>1</td>
</tr>
<tr>
<td>Cat 3-5 Hurricanes</td>
<td>1</td>
<td>.8429</td>
</tr>
</tbody>
</table>

Table 2.4: Coefficients applied to the favorability index, derived from multiple linear regression. Coefficients shown here are normalized by the maximum co-efficient.

The shear used in the favorability index is calculated at the time of the SSM/I pass and is derived from the six hourly resolution provided by SHIPS via linear interpolation. The same analysis techniques that are used for the SSM/I and shear are used for the combined favorability index.

### 2.2.3 GPS Dropsondes

The SSM/I and TMI TPW data provide an integrated water vapor value. Thus, there is no information regarding the vertical distribution of water vapor. Therefore, global positioning system (GPS) dropsonde data (Franklin et al., 2003) from the G-IV and P3 aircraft were used to assess how the water vapor content varies with height. The G-IV data were used for all TCs south of 35N and more than six hours from landfall from
1998-2005. The P3 data was used exclusively for Hurricanes Katrina and Rita. The G-IV deployed dropsondes in the outer storm environment, at radii similar to those used for the SSM/I TPW. The P3 dropsondes were deployed around the rainbands of Hurricanes Katrina and Rita and in the moat area, the region between the primary and secondary eyewalls, of Rita. For the statistical study from 1998-2005, TCs were divided based upon the criteria stated in the previous two sections, with the TC intensity and intensity changed determined from either 1200 UTC for a flight starting at 0600 UTC, 2100 UTC for a flight starting at 1500 UTC, or from 0000 UTC for a flight starting at 1800 UTC. For the Katrina and Rita portion, the dropsondes were used strictly to assess the large scale environmental water vapor distribution and atmospheric stability and the resulting impact on the rainbands of the two hurricanes.

For both the G-IV and P3 aircraft, the dropsondes had a temporal resolution of $\frac{1}{2}$ second. G-IV (P3) data were then interpolated onto a 100m (25m) vertical resolution from the surface to 11km (2.5km). Daily composite mean profiles were created for each flight to represent the TC environment during the time of the flight. This was done for both the statistical as well as the Katrina and Rita case studies. In the Katrina and Rita case studies, separate profiles were created for the outer environment and rainband area. Tables 2.5 and 2.6 provide the number of G-IV and P3 dropsondes used for this study.
Table 2.5: Number of G-IV flights (dropsondes) used in this study for intensifying, steady, and weakening tropical storms, category 1-2 hurricanes, and major hurricanes.

<table>
<thead>
<tr>
<th></th>
<th>Intensifying</th>
<th>Steady</th>
<th>Weakening</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Storms</td>
<td>31 (367)</td>
<td>17 (375)</td>
<td>5 (86)</td>
<td>43 (847)</td>
</tr>
<tr>
<td>Cat 1-2 Hurricanes</td>
<td>23 (477)</td>
<td>17 (370)</td>
<td>5 (100)</td>
<td>45 (921)</td>
</tr>
<tr>
<td>Cat 3-5 Hurricanes</td>
<td>11 (189)</td>
<td>18 (382)</td>
<td>21 (373)</td>
<td>50 (970)</td>
</tr>
</tbody>
</table>

Table 2.6: Number of RAINEX P3 and G-IV dropsondes used in the Katrina and Rita case study. P3 dropsondes were deployed between the rainbands while G-IV sondes were deployed in the outer storm environment.

<table>
<thead>
<tr>
<th></th>
<th>P3 Dropsondes</th>
<th>G-IV Dropsondes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Katrina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>August 27</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>August 28</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>Rita</td>
<td></td>
<td></td>
</tr>
<tr>
<td>September 21</td>
<td>34</td>
<td>21</td>
</tr>
<tr>
<td>September 22</td>
<td>9</td>
<td>22</td>
</tr>
</tbody>
</table>

2.3 High-Resolution Model Forecast Fields

During the RAINEX field program in August-September 2005, a mini-ensemble of high-resolution model forecasts was conducted in real-time. The model used is the 5th
generation of Penn State University/National Center for Atmospheric Research non-hydrostatic mesoscale model (MM5) with various initial and lateral boundary conditions from four different large-scale model forecast fields. The four large-scale models are from the Canadian Meteorological Center (CMC) (Cote et al., 1998), the Geophysical Fluid Dynamics Lab (GFDL) (Kurihara et al., 1995), the NCEP Global Forecast System (GFS) (Rhome, 2007), and the Naval Operational Global Prediction System (NOGAPS) (Rhome, 2007). Except for the GFDL, which is a coupled ocean-atmosphere model, these models are only atmospheric models, as is the MM5. The MM5 forecasts were used for aircraft mission planning during RAINEX. The model fields used in this study are from two of the real-time forecasts that captured some observed key features in Katrina and Rita, especially the rainband structure, which are most relevant to this study. In fact, the aircraft flights were directed in part with the guidance of these forecast fields in real-time. This study uses the GFDL conditions from 0000 UTC August 27-1200 UTC August 29, 2005 for the Katrina forecast and NOGAPS conditions from 0000 UTC September 20-1200 UTC September 23 for the Rita forecast as these were the conditions that produced the best forecast from the mini-ensemble for the respective storms. Both forecasts utilized a vortex following nested grid developed by Chen and Tenerelli (2007) with 3 nested grids of 15, 5, and 1.67 km horizontal resolution. Figure 2.1 shows an example of the nested grid used for the forecasts. Both forecasts also featured 28 vertical sigma levels, with higher resolution within the boundary layer. The Goddard microphysics scheme (Tao and Simpson, 1993) was used for both forecasts.
Figure 2.1: Sample model domains used for the MM5 Katrina and Rita Forecasts. Outer domain is fixed, while inner-two domains follow the vortex. For the forecasts, the domains were shifted to the west due to the location of Katrina and Rita.
Chapter 3: Environmental Water Vapor and TC Intensity Change

3.1 Water Vapor Distribution in the Tropical Atlantic

Water vapor content in the tropical Atlantic during the hurricane season is climatologically higher in the western part of the basin than in the eastern portions north of the inter-tropical convergence zone (ITCZ). Climatological hurricane season TPW, as defined as June through October, is around 50mm in the Caribbean and southern Gulf of Mexico with slightly lower values of 40-45mm in the northern Gulf and subtropical western Atlantic. A large north-south TPW gradient exists in the east Atlantic. Climatological TPW is around 50mm within the ITCZ and rapidly decreases to below 40mm north of the Cape Verde Islands, and to below 30mm near the Canary Islands (Fig. 3.1).

Figure 3.1: Climatological TPW in mm for the Atlantic Basin during the hurricane season calculated from the average of SSM/I data of June-October from 1988-2005. Magenta dots represent the locations of TCs with NOAA G-IV flights during the hurricane seasons from 1997-2005.

Pennington (2003) determined that tropical cyclogenesis occurs in regions where the TPW is high, either climatologically or anomalously. However, Pennington (2003)
did not examine how the intensity changed after the TC genesis. Here we will investigate
the developed TCs from the tropical storms to major category 3-5 hurricanes that were
flown by the NOAA G-IV from 1997-2005 with extensive dropsonde data (indicated by
the magenta dots in Fig. 3.1).

3.2 Statistical Relationship between Water Vapor and Intensity Change

TCs in the tropical Atlantic showed a positive correlation between increased
intensity and water vapor content. On average, category 3-5 hurricanes have the highest
water vapor content, while tropical storms have the least. Figure 3.2 shows the
climatological environmental TPW for tropical storms, category 1-2 hurricanes, and
category 3-5 hurricanes, as well as the composite mean TPW for intensifying, steady, and
weakening TCs. The definitions of intensifying, steady, and weakening TCs are provided
in Table 3.1.

<table>
<thead>
<tr>
<th></th>
<th>Intensifying</th>
<th>Steady</th>
<th>Weakening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Storms</td>
<td>&lt; 2</td>
<td>-2 to 2</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Cat 1-2 Hurricanes</td>
<td>&lt; 4</td>
<td>-4 to 4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Cat 3-5 Hurricanes</td>
<td>&lt; 5</td>
<td>-5 to 5</td>
<td>&gt; 5</td>
</tr>
</tbody>
</table>

Table 3.1: Definitions of intensifying, steady, and weakening TCs for tropical storms,
category 1-2 hurricanes, and category 3-5 hurricanes. Values in table represent change in
MSLP for the 12 hours after the data observation.

In addition to the relation between intensity and TPW, there is a clear relation
between intensity change and TPW. Intensifying TCs had composite TPW values above
the TC climatological mean for all three groups. Weakening TCs had TPW below the
climatological mean. The composite TPW for steady and weakening TCs in hurricane
categories were similar. This suggests that TPW may not be sufficient to distinguish
weakening and steady-state cyclones. This is further demonstrated by Fig 3.3, which shows the probability density functions (PDFs) of TPW and 12-hr intensity change for the three intensity groups. There is no clear trend for the tropical storms, with a better trend for storms of hurricane intensity. The correlation coefficients (denoted as r throughout the thesis) between TPW and intensity change demonstrate this point. For tropical storms, r=.16 (r² = .04), .29 (r² = .084) for category 1-2 hurricanes, and .28 (r² = .078) for category 3-5 hurricanes. All correlations presented in this thesis are significant to the 99 percent confidence level. TPW and intensity change for TCs of hurricane intensity are more correlated than for tropical storms. Intensification, especially rapid intensification, tends to occur once hurricane intensity is reached in anomalously moist environments. Weakening tends to occur within a dry environment. However, intensification (weakening) can still occur in a dry (moist) environment. These results show that TPW alone cannot explain all of the processes through which water vapor affects intensity change.
Figure 3.2: Comparison mean TPW from 1987-2005 for tropical storms (white), category 1-2 hurricanes (gray), and category 3-5 hurricanes (black), along with the comparison of the mean of intensifying (group A), steady (group B), and weakening (group C) cyclones within each group.
Figure 3.3: Scatterplots and probability distributions of water vapor and corresponding intensity change for (a) tropical storms, (b) category 1-2 hurricanes, and (c), category 3-5 hurricanes. Vertical black lines represent mean TPW for each group. Includes all storms from 1987-2005. Contours labels denote the probability contours.
Figure 3.4: Composite mean RH TC soundings from the surface to 11km from 1998-2005. Tropical storms are denoted by the red line, category 1-2 hurricanes by the black, category 3-5 hurricanes by the blue, and the Jordan mean sounding from the West Indies for the months of July through October in the dashed magenta.
The SSM/I data was unable to provide information regarding the vertical distribution of water vapor. Therefore, GPS dropsondes are used. GPS dropsondes (Fig 3.4) show that the climatological TC environment is closer to saturation than the mean sounding from the West Indies for the months of July-October as derived by Jordan (1958) in the middle levels of the troposphere. Additionally, the composite mean TC vertical profiles of RH for each of the intensity groups show that the mean TC environment is more moist between 3-6 km than the 1958 Jordan Sounding (Jordan, 1958). Mean RH values are 5-10 percent higher in the TC environment.

Composite profiles from each of the three intensity groups (Fig 3.5) show a similar signal as that associated with the TPW data. Intensifying TCs had the highest RH from the top of the boundary layer to about 7km. For tropical storms and category 1-2 hurricanes, weakening TCs had the lowest RH values. For category 3-5 hurricanes, weakening and steady TCs had similar composite RH profiles. These results, shown in Fig 3.5, show that the water vapor content in the middle troposphere is correlated with intensity change. The difference in the composite mean RH profiles for intensifying and weakening TCs between 3-8 km is significant to the 95 percent confidence level for all three groups as determined by the Kolmogorov-Smirnov test. However, water vapor alone cannot explain TC intensity change completely, especially in category 3-5 hurricanes where steady-state storms have a similar composite vertical moisture profile as do weakening storms. To attempt to explain more of the variance, the study progresses to quantify the combined effects of water vapor and vertical wind shear.
Figure 3.5: Composite mean relative humidity profile from the GPS dropsondes from 1998-2005 for intensifying, steady, and weakening TCs.
3.3 Combined Effects of Water Vapor and Vertical Wind Shear

Before discussing the combined impacts of water vapor and vertical wind shear, the effect of wind shear alone needs to be briefly discussed. As was for the case with TPW, the environmental vertical wind shear and TC intensity change are correlated. Fig 3.6 shows the PDFs of the SHIPS vertical wind shear and the 12-hr intensity change. The PDFs show a general trend of intensification in low shear environments and weakening in high shear environments. However, for the category 3-5 hurricanes, there are many cases of weakening despite low shear environments. The correlation is the weakest for category 3-5 hurricanes with \( r = 0.27 \) \( (r^2 = 0.072) \). Category 1-2 hurricanes are the most correlated with \( r = 0.40 \) \( (r^2 = 0.160) \). Tropical storms are in the middle with \( r = 0.33 \) \( (r^2 = 0.109) \).

To address a combined effect of TPW and shear, equation 2.1 and the coefficients from table 2.4 are used. These resulting favorability points are correlated with the 12 hour intensity change. Figure 3.7 shows the PDF of favorability points and 12 hour intensity change. While the relation for the tropical storm group is not much different than for shear alone with \( r = 0.34 \) \( (r^2 = 0.116) \), the signal is strengthened for the TCs that have reached hurricane intensity. An unfavorable environment in these groups tends to result in weakening, while intensification, especially rapid intensification, occurs in a moist, low shear environment. The correlations are higher, with \( r = 0.48 \) \( (r^2 = 0.230) \) and \( 0.37 \) \( (r^2 = 0.134) \) for the category 1-2 and 3-5 groups respectively and more of the intensity change variance is explained.
Figure 3.6: Probability distributions of vertical wind shear and corresponding intensity change for tropical storms (a), category 1-2 hurricanes (b), and category 3-5 hurricanes (c). Vertical line represents mean shear for each group. Time period is from 1987-2005. Contour labels denote the probability contours.
These results confirm some observational evidence in individual TCs, such as in Hurricane Georges (1998) (Cangialosi and Chen 2007) and Ivan 2004 (Stewart, 2005). While dry air creates an environment that is more favorable for weakening, it needs to be entrained into the inner-core in order to directly weaken the TC. Vertical shear may allow dry air to intrude into the core as the shear disrupts the deep convective activity. The convective activity prevents the dry air from intruding as the processes of entrainment and detrainment result in modification of the dry air as it is entrained into the circulation.
When the convective activity is disrupted by the shear, the dry air can reach the core, causing weakening of the TC. This is demonstrated by the example from Hurricane Georges provided in Fig 3.8, which shows a series of SSM/I TPW passes from Hurricane Georges, along with the wind shear from SHIPS and the best track intensity. On September 18 and 19, dry air was present in the outer storm environment. The shear was low and the dry air did not penetrate the core. The wind shear increased on September 20. At this time, as demonstrated in panels c and d, the dry air was able to penetrate the core of the hurricane. The result was Georges experiencing a 29 hPa rise in pressure between 1200 UTC September 20 and 0000 UTC September 21, as shown in panel f.
Figure 3.8: Four storm centered SSM/I passes of Hurricane Georges from 2230 Sept 18 (a), 1106 Sept 19 (b), 0027 Sept 20 (c) and 1240 Sept 20 (d). The contouring for the plots is every 10mm. The SHIPS vertical wind shear in m s$^{-1}$ is in panel (e) and the best track intensity in hPa is in panel (f). The black dots represent in panels (e) and (f) correspond to the times of the SSM/I passes. Dot a corresponds to the pass in panel (a), dot b to panel (b), dot c to panel (c) and dot d to panel (d).
3.4 Summary

Environmental water vapor has a significant effect on TC intensity change. Intensifying TCs tend to have anomalously high water vapor content, while weakening TCs have low water vapor content. However, for TCs of hurricane intensity, there is little difference between weakening and steady TCs. Vertical wind shear was required to allow for the water vapor to significantly impact TC intensity. The variance explained by considering the combined effects of vertical wind shear and water vapor is about 3 times greater for tropical storms and category 1-2 hurricanes and nearly 2 times higher for category 3-5 hurricanes, than when considering water vapor alone. A possible reason for this is that vertical shear may allow for the environmental dry air become entrained into the TC core by disrupting the convective processes that would otherwise modify the dry air.

However, there is still a lot of intensity change unexplained by the analysis presented in this chapter. This is especially true for category 3-5 hurricanes. Within the favorable environment regime, there are still many TCs that weaken. This is partially due to other factors, including SST variations; however, water vapor can still affect intensity through a mechanism which was not yet accounted for. Enhanced water vapor content within the rainbands can enhance rainband intensity, which can then trigger an eyewall replacement cycle (Emanuel, 1995, Nong and Emanuel, 2003, Lonfat, 2004, Ortt and Chen, 2006), causing significant changes in intensity (Willoughby et al., 1982). The remainder of this thesis will evaluate the relationship between environmental vapor and rainbands. Specifically, the issue of how the environmental water vapor distribution...
affects rainband activity will be carefully evaluated, along with a hypothesized mechanism for how rainbands can lead to the formation of a secondary eyewall.
Chapter 4: Effects of Water Vapor on Hurricane Rainbands

4.1 Hurricane Rainband and Intensity Change Experiment (RAINEX)

The 2005 hurricane season provided a large amount of data to address whether the environmental water vapor distribution affects TC rainband structure, including data from the Hurricane Rainband and Intensity Change Experiment (RAINEX) (Houze et al. 2006, Chen 2006). RAINEX was the first field program to simultaneously sample the inner-core and rainbands with three P3 aircraft, while G-IV operational missions sampled the outer storm environment. Previous observational studies documented the structure of eyewall, inner bands, and outer rainbands, respectively (e.g., Willoughby et al. 1982, Powell 1990a and b, Samsury and Zisper 1995). However, the observations were not collected simultaneously over all three regions, which limited the investigation on the interaction of the environment, rainbands, and the inner-core. Well formed rainbands have a negative impact on the inner-core due to the convective downdrafts, which transport low theta-e to the surface (Powell, 1990b) and affect the inflow to the inner-core. If rainbands are concentric about the eyewall, inflow into the eyewall would be reduced (Samsury and Zisper, 1995). These two processes can disrupt the eyewall and cause temporary weakening (Willoughby et al., 1982).

The RAINEX observations consisted of multi-aircraft coordinated missions into Hurricanes Katrina, Ophelia, and Rita with the National Oceanic and Atmospheric Administration (NOAA) and the Naval Research Laboratory (NRL) P3 aircraft. The two NOAA P3 aircraft penetrated the inner-core of the hurricanes and some rainbands, while the NRL P3 primarily sampled the principal rainband outside of the core, though the
moat region, the area between the primary and secondary eyewalls, of Hurricane Rita was sampled on September 22 by the NRL P3 (Houze et al., 2007).

During RAINEX we also conducted high-resolution model forecasts of Katrina, Ophelia and Rita using MM5 in real-time for mission planning. These forecasts were vital for the development of the flight plans during each storm, as well as allowing for a potentially more thorough evaluation of the features observed after each mission, if the simulations were able to reproduce the observations. The extensive targeted sampling and flight patterns in Rita while the storm underwent an eyewall replacement cycle were planned ahead based on the high-resolution model forecast.

In this study we examine the model output of Katrina and Rita. They were both category 5 hurricanes, but evolved differently with some distinct structures in the Gulf of Mexico. Both model output and observations have indicated that there is noticeable difference in the hurricane rainbands in the two storms. These full physics model results will provide some insights that are not possible from previous idealized modeling studies on hurricane rainbands, e.g. Guinn and Schubert 1993, Montgomery and Kallenbach 1997, using models with dry dynamics. Thus, while they were able to address rainband and eyewall issues such as potential vorticity (PV) redistribution, they were unable to account for the generation of PV through the moist convective processes, which are critical for the rainband and eyewall interaction (Kossin et al. 2000).

### 4.2 Hurricanes Katrina and Rita

Hurricanes Katrina and Rita were two of the most intense hurricanes ever recorded in the Atlantic Basin. At its peak, Katrina had a minimum central pressure of
902 hPa (Knabb et al. 2005) while Rita had a minimum central pressure of 897 hPa, making it the most intense hurricane ever recorded in the Gulf of Mexico (Knabb et al. 2006). Figures 4.1 and 4.2 show the track and intensity of the two hurricanes.

Hurricane Katrina, in August 2005 formed from the remains of Tropical Depression 10 in the eastern Bahamas on August 22 (Knabb et al., 2005). Katrina intensified into a tropical storm the next day and continued to slowly intensify, reaching category 1 hurricane status as it was making landfall in the Miami area.

Figure 4.1: MM5 and best track for Hurricanes Katrina (a) and Rita (b). Black (red) dots are the best track (MM5) positions every 6 (1) hours.
Katrina was expected to spend 12 hours over south Florida and weaken to a minimal tropical storm. Instead, Katrina moved to the south of the forecast track at a faster than forecast forward speed. This enabled Katrina to maintain most of its intensity while crossing the peninsula, weakening only to 30 m s\(^{-1}\). Katrina then resumed its intensification in the Gulf of Mexico, regaining hurricane status after one hour over the Gulf. Category 3 status was attained 24 hours later, and category 5 status followed 30 hours after reaching category 3 status. Katrina peaked six hours later, at 1800 UTC August 28, 2005 with maximum sustained winds of 77 m s\(^{-1}\) and a central pressure of 902hPa. Soon after, Katrina began to weaken rapidly and made landfall just south of New Orleans at 1100 UTC August 29 with maximum sustained winds of 56 m s\(^{-1}\) and a minimum central pressure of 920hPa. Final landfall in Mississippi occurred four hours later with maximum sustained winds of 54 m s\(^{-1}\) and a pressure of 927hPa.

Rita formed in a similar location as Katrina, in the eastern Bahamas at 0000 UTC on September 18 (Knabb et al. 2006). Rita initially intensified at a faster rate than
Katrina, reaching tropical storm status later that morning. Rita became a hurricane early on September 20 in the Florida Straits. Hours after reaching hurricane status, Rita passed about 60km south of Key West. At this time, Rita had attained category 2 intensity.

Once in the Gulf of Mexico, Rita intensified rapidly, becoming a major hurricane early on September 21 and peaked as a category 5 hurricane with maximum winds of 79 m s\(^{-1}\) and a central pressure of 897mb at 0600 UTC, September 22, making Rita the most intense hurricane ever recorded in the Gulf of Mexico, breaking the record set by Katrina just a month earlier. Like Katrina, Rita underwent significant weakening prior to making landfall. In the afternoon of September 22, Rita underwent an eyewall replacement cycle (EWRC). During this time, Rita weakened to a category 4 hurricane. On September 23, vertical wind shear increased, causing Rita to weaken further. At landfall near the Texas/Louisiana Border, Rita's maximum sustained winds had decreased to 51 m s\(^{-1}\) and the pressure had risen to 937hPa.

The MM5 forecasts produced similar intensity trends when compared to the observed storms. However, there were differences. The MM5 had a peak maximum wind speed about 15 m s\(^{-1}\) lower than the observed storm. This is due to the eyewall replacement in the MM5 occurring a few hours prior to the observed. A second difference is that the MM5 hurricanes made landfall at a greater intensity than the observed. In the Rita case, this is likely due to the storm making landfall about 24 hours prior to the observed, not allowing the vertical shear to become established over the storm. In Katrina, the MM5 vertical shear was lower than the observed (not shown).

Despite the similarities in intensity, the two hurricanes were very different in terms of their rainband structure and evolution. Although Hurricane Katrina may have
gone through an eyewall replacement cycle (EWRC) early on August 27, which cannot be fully confirmed based on very limited data prior to RAINEX flights, it maintained a single eyewall over most of the Gulf until the time of landfall. In contrast, Rita, as previously stated, underwent a major EWRC shortly after reaching peak intensity. It is hypothesized that Rita had greater circularity of rainband convection, which allowed for concentric eyewalls and an EWRC.

4.3 Environmental Water Vapor Distributions for Katrina and Rita

4.3.1 Outer Environment

The TPW in the outer environment, in this case defined as 250-600km from the center, which is slightly different from that in Chapter 3 due to the large size of the two hurricanes, of Katrina exceeded 60 mm (Fig. 4.2). That is higher than the mean of 56-57 mm for the major hurricanes as shown in Ch. 3. In contrast, the outer environment for Rita was significantly drier with a TPW on average from 51-56 mm, with some values were as low as 40mm to the north and west of the center.

The TPW values near and within Katrina and Rita are much higher than from the statistical analysis in the previous chapter, which was about 46 mm. A direct comparison between SSM/I and TMI may not be appropriate since there may be differences between the two instruments. However, comparing the two storms with the same TPW data from TMI should be reasonable. The comparison shows that the mean TWP in the outer environment of Katrina was about 3-5 mm higher than that in Rita. Table 4.1 provides the mean TPW from the outer environments from each TPW pass where there was 50 percent
data coverage and the large scale TPW of both the hurricane circulation and outer environments are shown in Fig 4.3 and Fig 4.4.

The TMI data demonstrates different large scale water vapor distributions for Katrina and Rita. Katrina is in a relatively moist environment and Rita is in a relatively dry environment. One limitation in TMI TPW is that it cannot tell where the dry air is located vertically in the troposphere. The composite of the GPS dropsonde data from the G-IV flights around the storm indicate that the main difference in the water vapor distributions of the two storms is located within the middle troposphere. This is same area where the differences are typically located in the TC environment. Figure 4.5 shows the composite mean RH profiles from the outer environments of Katrina and Rita, along with the category 3-5 hurricane composite mean profile from 1998-2005.

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<td>Rita</td>
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Table 4.1: Mean TPW in mm from the outer storm environments (250-600km) for Hurricanes Katrina and Rita. Only the times where the outer environment has at least 50 percent data coverage are included.
Figure 4.3: TMI TPW for Hurricane Katrina from 2048 UTC August 27 (a), 0330 UTC August 28 (b), and 2130 UTC August 28, 2005 (c).
The outer environment of Hurricane Rita was anomalously low when compared to the 1998-2005 climatology for category 3-5 hurricanes, especially between 5 and 8 km, where RH values are about 20-25 percent less than the composite mean for September 21, and about 10-15 percent lower the next day. In contrast, Katrina on August 27 was in an outer environment that was about 5-10 percent more moist the mean and about 10-20 percent above the composite mean on August 28. These results demonstrate the fact that
the outer environment that Hurricane Katrina was located in was anomalously moist, while the environment that Rita was in was anomalously dry.

The trends shown by the observations were reproduced by the MM5 forecasts, though the exact details do vary somewhat. Figure 4.6 shows the composite MM5 outer environmental RH vertical profiles for Katrina and Rita at the times of the dropsonde analysis. The composite mean RH for Rita for both days within the middle troposphere was 10-20 percent below that of Katrina. The environment surrounding Rita had a composite RH value of about 45-50 percent for both days compared to 60-70 percent for Katrina, though the absolute RH values for both storms were higher than those observed. Of note from the MM5 is the boundary layer below 1km. The composite RH values from the boundary layer are very similar for the two storms and did not vary with time. The values are about 5-10 percent above the observations. The observed composite RH peaked at ~1km with a composite value of 80-85 percent, while the MM5 output had a composite value of 90-95 percent.
Figure 4.5: Daily composite of the G-IV dropsonde profiles in the outer environment (250-600km) of Hurricanes Katrina on 27 August (cyan) and 28 August (blue) and Rita on 21 September (magenta) and 22 September (red). The profile in black is the mean for category 3-5 hurricanes from 1997-2005 mean sounding from Chapter 3.

Figure 4.6: Same as in Fig. 4.5 expect from the MM5 output.
**4.3.2 Water Vapor in between Rainbands**

Although the TMI TPW indicates little difference in TPW between rainbands (likely due to the ¼ degree resolution of the TMI data, which is too coarse to resolve areas between rainbands), RH data from the P3 dropsondes from the rainband regions show a marked difference between the two storms. RH values just above the boundary layer in Rita were about 5-10 percent higher than those in Katrina. The MM5 composite sounding from the rainbands shows similar results, though the differences between Katrina and Rita are slightly less than those observed. Figure 4.7 shows the observed and MM5 daily composite rainband RH profiles for Katrina and Rita.

Comparisons with the long term climatology cannot be made with regards to the rainband dropsonde data. RAINEX was a unique field program where extensive sampling was conducted within the rainbands. The standard P3 mission typically samples the eye and eyewall, resulting in a very small sample from the rainbands.

Figure 4.7: Composite RH vertical profiles from the rainband regions (defined as area between convective rainbands located outside of the radius of hurricane force winds) for Hurricanes Katrina and Rita from the P3 dropsondes (a) and MM5 (b). The color scheme is the same as used in Fig. 4.5.
4.3.3 Evolution of Water Vapor Distribution

Since MM5 was able to reproduce the observed 3-dimensional water vapor distributions of Katrina and Rita with some accuracy, the model output will be used to study the evolution of the water vapor. Fig. 4.8 shows the radial-time plot of the simulated RH at 600 hPa level for Katrina and Rita. The outer environment of Rita remained dry with RH in the middle troposphere remaining between 40 and 50 percent throughout the forecast period. The environment remained relatively moist for Katrina, with RH values remaining above 50-60 percent throughout the forecast period. RH values within the rainbands were higher for Rita by about 5-10 percent in the lower parts of the troposphere, until late on August 28. At this time, the RH within the rainbands was similar to those from Hurricane Rita, with RH values between 95-100 percent. Fig. 4.8b demonstrated the persistent nature of the sharp moisture gradient between Hurricanes Rita's rainbands and outer environment, and the weak gradient that existed between the two areas of Katrina within the middle troposphere.
4.4 Rainband Structures

4.4.1 Circularity of rainbands around the storm

To quantify the rainband structures and patterns, an index measuring the rainband circularity is introduced. This index is defined as the fraction of rainrate greater than 12.5 mm h$^{-1}$ at a given radius outside of the eyewall. It is represented mathematically as follows.

$$C(i) = \frac{r_{>12.5}(i)}{r_{r}(i)}$$  \hspace{1cm} (4.1)

where $C$ is the circularity, $r_{>12.5}$ is the number of data pixels or model grid points that have a rainrate greater than 12.5 mm h$^{-1}$, $r_{r}$ is the total number of pixels or model grid points, and $i$ represents the successive 5km radii from 0 to 200km.
4.4.1a. Katrina

Rainbands in Katrina extended outward from the center to radii reaching about 400km. Figure 4.9 shows the TMI rainrate imagery and rainband circularity for Hurricane Katrina from 0325 UTC and 2130 UTC, August 28 2005. In both instances, there is only a single eyewall present. While there is a slight peak in rainband circularity outside of the eyewall at 0325 UTC, this appears to be an artifact of the data as the horizontal map does not show any outer rainband with high circularity. At 2130, there were no outer rainbands with circularity greater than .5. The circularity value of .5 is important as National Hurricane Center operational practices would qualify the band as a candidate to be a secondary eyewall (Williamson et al., 2007). The rainbands tended to spiral directly into the center instead of forming a concentric convective ring around the center. Rainband circularity outside of the eyewall peaked at about .25 between 75-85km from the center (about 50km outside of the eyewall) and was below .1 at all radii exceeding 100km from the center. In addition, there was not an outer wind maximum associated with Katrina at this time, as depicted by the flight level data from the NOAA reconnaissance aircraft. Figure 4.10 shows that there was a single peak in flight level winds associated with the eyewall and no outer wind maximum.

The MM5 forecast for Katrina produced a primary eyewall structure while it also showed a secondary peak in very close proximity right outside of the eyewall. However, there was no clear separation of the two peaks. Figure 4.11 shows a horizontal rainrate map from the MM5 output and a circularity profile from 2100 UTC August 28. It showed many connecting inner bands, which may explain why the two peaks are not separated. Fig. 4.12 shows a time-radial diagram of azimuthally averaged rainrate from 0000 UTC
August 27 to 0000 UTC August 30, which indicates that the inner band peak was not persistent and never formed into a secondary eyewall. In addition, this band was connected to the eyewall and not separate as is a secondary eyewall. The model forecast overestimated the storm intensity right before landfall, which was largely due to the fact that model produced a smaller eye than that was observed in Katrina. Outside of the secondary eyewall, rainband circularity remained below .2. This was higher than indicated by the TMI data. However, no rainbands showed signs of forming into a true secondary eyewall.
Figure 4.9: TRMM TMI rainrate (mm/h) of Katrina from 0325 UTC August 28, 2005 (a) and rainband circularity of Katrina (c and d) from the times of the rainrate images (a and b). Black line represents secondary eyewall candidate threshold of .50.
Figure 4.10: Flight level data from NOAA 43 for Hurricane Katrina. Blue represents flight level winds (kts), black represents SFMR surface winds (kts), while the green and dashed red lines represent the temperature and dewpoint (K).
Another indicator that the concentric ring present at 2100 UTC on August 28 never developed into a secondary eyewall is indicated by the potential vorticity evolution of this feature. Kossin et al. (2000) demonstrated that a secondary eyewall is associated with an elevated ring of potential vorticity. In the Katrina forecast, this elevated ring of potential vorticity never existed. Figure 4.13 shows a time-radius diagram of the azimuthal average of the common log potential vorticity (PV) scaled by a factor of 30 from the MM5 forecast for Katrina. A well-defined peak of PV associated with the eyewall was present. Outside of the eyewall, PV largely decreases monotonically with increasing radius, with no indication of an elevated secondary ring. Without this elevated ring of PV, a secondary wind maximum, the definition of a secondary eyewall (Willoughby et al., 1982) should not be present since vorticity is the derivative of the wind. Aircraft flight level data, along with the MM5 output show no indication of a well-defined secondary wind maximum outside of the primary eyewall. The transient concentric band not forming into a concentric eyewall is not unprecedented. Willoughby et al. (1984) also found through numerical modeling simulations that not all concentric ring evolve into a secondary eyewall, but that persistent concentric rings tend to form into a secondary eyewall. These results from RAINEX support that finding from 23 years ago.

Based upon the results presented in this section, it can be concluded that Katrina's rainbands lacked persistent circularity outside of the eyewall. The rainbands did not form into a secondary eyewall from after the possible eyewall replacement early on August 27, prior to the RAINEX surveillance.
Figure 4.11: Same as Fig 4.9 except for the MM5 output at 2100 UTC August 28, 2005.
Figure 4.12: Time radius diagram of rainband circularity for Hurricane Katrina from MM5 output from 0000 UTC August 27 to 1200 UTC August 29, 2005.

Figure 4.13: Time-radius diagram of the azimuthal average of the common log of the potential vorticity scaled by a factor of 30 (PV) for Hurricane Katrina from MM5 output. Times are the same as in Fig 4.12.
4.4.1b. Rita

Rainbands in Hurricane Rita were confined closer to the center than those of Katrina. The rainbands also had greater circularity than Katrina. Figure 4.14 shows TMI rainrate passes from Rita at 0812 UTC September 22, and 1348 UTC September 23, 2005, along with the rainband circularity. On September 22, Hurricane Rita had an eyewall, as depicted by the intense ring of rain surrounding the eye, and two rainbands with circularity greater than .50. Outside of the second outer concentric rainband, about 80km from the center, there was a band with circularity of approximately .40. Rainband circularity between 100-150km ranged between .10 and .20. This was higher than in Katrina. On September 23, the primary eyewall had dissipated, leaving the secondary eyewall as the new primary eyewall.

The aircraft flight level winds from September 22 indicated that there was a secondary wind maximum associated with the inner of the two rainbands. Therefore, it can be concluded that Rita did in fact have a concentric eyewall structure. During the next 24 hours, this secondary eyewall would become the dominant eyewall. Rita proceeded to weaken from a peak intensity of 79 m s\(^{-1}\) to 64 m s\(^{-1}\) within a 12 hour period on September 22. Figure 4.15 shows a sequence of flight level wind profiles from the Air Force reconnaissance aircraft. Initially, a single wind maximum is evident as winds decrease monotonically with radius outside of the eyewall. As the day progresses, a secondary wind maximum develops within the concentric rainband. In the latter part of the day, the secondary eyewall became the primary eyewall as the primary eyewall collapsed.
The MM5 forecast of Rita was also able to accurately reproduce the observed features. At 0800 UTC, The MM5 forecast showed a clearly defined eyewall, along with a second rainband with circularity exceeding .50. This is shown in Fig 4.16. Additionally, the MM5 forecast correctly forecast the eyewall replacement that occurred on September 22. Figure 4.17 shows the rainband circularity time-radius Diagram for Rita from the MM5 output. Initially, Rita consists of a single eyewall without any rainbands with high circularity. Around midday on September 21, the circularity of a rainband located about 50-75km outside of the eyewall began to increase. Around 0000 UTC September 22, the rainband's circularity exceeded the 50 percent eyewall candidate threshold. By 1800 UTC, the inner eyewall had dissipated and the outer eyewall became the new eyewall. Also of interest, the MM5 forecast indicated another rainband with circularity exceeding the .50 threshold as the storm was making landfall. This was not present in the TMI analysis, though the MM5 was too fast on the track. As the actual Rita approached the coast, a TMI analysis was not possible since TMI data is not available over land. However, WSR-88D radar from Lake Charles in the hours before landfall shows that there was in fact a third rainband with high circularity developing as Rita was making landfall. Figure 4.18 shows a reflectivity image from 0005 UTC, September 24. A well-defined eyewall is present, along with a well-defined rainband with high circularity outside of the eyewall. This demonstrates that the MM5 was not only able to reproduce the observed eyewall replacement, but a second occurrence of a rainband with high circularity.

To further demonstrate the fact that Rita's rainbands did form into a secondary eyewall in the MM5, a PV analysis is presented in Fig 4.19. The azimuthal average of the
scaled PV for Rita from the MM5 output shows a well-defined eyewall at the start of the forecast period. On September 21, an elevated ring of PV began to develop in association with the rainband discussed previously. Late on September 22, the PV increased to levels equal with that of the original eyewall. The PV in the secondary eyewall then exceeded that of the primary eyewall as it dissipated late on September 22. Additionally, the rainband that formed on September 23 has an associated PV peak. This suggests that Rita might have underwent another EWRC had the hurricane not have crossed the coasts of Texas and Louisiana.
Figure 4.14: TMI rainrate images (mm/h) of Hurricane Rita from 0812 UTC September 22 (a) and 1348 UTC September 23 (b), 2005 along with rainband circularity (c and d) from the times of the rainrate images. Black line represents .50 circularity secondary eyewall threshold.
Figure 4.15: 700mb Air Force Flight level data for Hurricane Rita on September 22, 2005 from 0650-0740 UTC (a), 1050-1140 UTC (b), 1850-1940 UTC (c) and 2310 to 0000 UTC September 23 (d). Blue represents flight level winds (KT), while the green and dashed red lines represent the temperature and dewpoint (K).
Figure 4.16: Same as Fig 4.14, except for MM5 output from 1100 UTC September 22.
Figure 4.17: Time-radius diagram of rainband circularity from MM5 output for Hurricane Rita from 1200 UTC September 20, 2005 to 1200 UTC September 23, 2005.

Figure 4.18: WSR-88D radar reflectivity (DBZ) from Lake Charles, Louisiana of Hurricane Rita from 0005 UTC, September 24, 2005.
It was demonstrated that Katrina was located within a moist environment, while Rita was located within a dry environment. The radial moisture gradient between the rainbands and the outer environment was greater in Rita than Katrina. In addition, the rainbands of Rita had higher circularity than those of Katrina and were able to form into a secondary eyewall. A possible mechanism through which the environmental water vapor produced these patterns is atmospheric stability.

The first evaluation on the atmospheric stability that is presented is the potential instability. If there is no potential instability, convection cannot occur. Figure 4.20, shows environmental theta-e/saturation theta-e (theta-e*) composite profiles from the G-IV dropsondes. The potential instability is approximately the integral of the area between the vertical line representing the surface theta-e and the theta-e*. The dry outer environment
of Hurricane Rita was characterized by little to no potential instability while the environment of Katrina had relatively high potential instability. These results would suggest that this was the mechanism through which the atmosphere restricted the rainbands. However, the same analysis conducted on the MM5 output disproves this theory. The MM5 forecasts produced an outer environment with higher potential instability than indicated by the observations. Additionally, there was little difference between the two hurricanes. Figure 4.21 shows the MM5 output theta-e/theta-e* daily composite mean profiles.

Since the MM5 produced the observed features, despite higher than observed potential instability for Rita, it can be concluded that potential instability differences were not responsible for the differing rainband patterns. However, it was shown in the previous two figures that potential instability is dependent upon the boundary layer. Since the MM5 was too moist within the boundary layer, it produced an environment with high potential instability. Therefore, any stability differences between Katrina and Rita must be due to differences at higher levels of the troposphere. To address this issue, an index, the Moist Stability Index (MSI) was created.

The MSI was initially intended to be a combination of the Total Totals and K Indices (see Sturtevant, 1995 for more information on these two indices). However, the use of the 850hPa level proved to be inappropriate for the MM5 simulations due to the small variations in moisture near the boundary layer. Therefore, the index was adjusted to consider strictly the middle portions of the troposphere and is defined as
\[ \text{MSI} = (T_{700} - 3T_{500} - T_{400}) + (TD_{700} + TD_{500} + TD_{400}) \] (4.4.1)

with \( T \) representing the temperature and \( TD \) representing the dewpoint temperature and the subscripts representing the pressure levels used for the index in hPa.

Figure 4.20: Daily composite mean theta-e/theta-e* profiles from GPS dropsondes for Hurricanes Katrina on August 27 (a) and 28 (b) and Rita on September 21 (c) and 22 (d) Vertical line represents theta-e at surface.

Figure 4.21: Same as Fig 4.20 except for the MM5 forecasts.
Figure 4.22 shows the observed and MM5 MSI values for Katrina from August 27 and 28 and Rita from September 21 and 22 from the outer storm environments. While the MM5 MSI was higher than the observed for Rita, both the model and observations show that the environment of Rita was more stable than that of Katrina. The MSI for Rita was 5-10K lower than that of Katrina in the MM5 and about 20K lower in the observations. The cause of the differences between the observations and MM5 were due to the MM5 moisture being higher than the observed, even within the middle troposphere. However, the differences were not enough to affect whether or not convective activity could occur within the outer environment of Rita.

The evolution of the atmospheric stability is now evaluated using the MM5 output. Results demonstrate that not only was the environment around Katrina more unstable than that of Rita, but that there was a weaker radial gradient of stability present in Katrina than Rita. The stability gradient between Rita’s rainbands and the outer environment was very sharp as instability decreased between 150 and 300km from the center (Fig 4.23). In Katrina there was a gradual decrease in instability with increasing radius. Furthermore, the outer environment in Katrina was characterized by less than the climatological mean stability, derived from the Jordan Sounding, while Rita's stability was greater than the climatological tropical Atlantic mean outside of 300-400km. Figure 4.23 shows time-radius diagrams of the azimuthally averaged MSI for Katrina and Rita, summarizing the differences in stability within the outer environments that the storms were located in.
Figure 4.22: Observed (black) and MM5 (red) daily composite mean MSI of Hurricanes Katrina (left) and Rita (right) within the outer storm environment. Observed mean was derived from GPS dropsondes.

The above mentioned differences in atmospheric stability were well-correlated with the areas where the rainbands were located. For both Katrina and Rita, the organized outer rainbands were not located at radii beyond the MSI 10K radius. Negligible precipitation occurred beyond the MSI 2.5K radius. In the Katrina case, the 2.5K contour was greater than 400km from the center later on August 27 and early on the 28th, before shifting inward as the storm neared the coast of Louisiana. In Rita, this radius remained between 300 and 350km throughout the duration of the time period analyzed in this study. This is shown in Fig 4.23, which shows the azimuthally averaged rainrate along with the 2.5 and 10K MSI contours Additionally, the outer rainbands in Rita formed inside the radius of tropical storm force winds (not shown), allowing for the bands to be more circular in nature due to the circulation of the wind field. In the case of Katrina, the MSI 10K radius is outside of the tropical storm wind radii, allowing for the rainbands to have less circularity. This suggests that the radius of the 10K MSI in relation to the
circulation of the hurricane itself value may be critical to determining whether or not the rainbands will have high circularity.

Figure 4.23: Azimuthally averaged MM5 MSI Hurricanes Katrina (a) from 0000 UTC August 27 to 0000 UTC August 30 and Rita (b) from 1200 UTC September 21 to 1200 UTC September 23. The white contour represents the Jordan Mean Sounding MSI of 2.5K.

Figure 4.24: Azimuthally averaged MM5 rain rate overlaid with 2.5K (white) and 10K (magenta) MSI contours of Hurricanes Katrina (a) and Rita (b). The times are the same as in Fig 4.23.
4.5 Development of Moat Regions

The study has established the differences in the 3-dimensional water vapor structures as well as the rainband distributions in Katrina and Rita. The study will now suggest how the rainbands can form into a secondary eyewall. One likely reason for Rita's rainbands forming into a secondary eyewall lies in the region between the eyewall and the secondary circular rainband. This area, known as the moat, is believed to be critical for the formation of a secondary eyewall (Kossin et al., 2000).

The moat region is believed to be a region of descending motion, producing a drier troposphere than the convective regions of the TC (Houze et al, 2007). Figure 4.25 shows a skew-T diagram of the moat region from Hurricane Rita during the afternoon of September 22. The lowest parts of the troposphere are nearly saturated. However, above 800mb, the dewpoint decreases to about 5K below the temperature. Unfortunately, there is not a similar dataset from Katrina; thus, comparisons cannot be made between the two hurricanes using the observations. However, comparisons can be made with the MM5 forecasts since Rita had a well-defined moat and Katrina had, at times, a moat-like region of relatively weak rainfall outside of the eyewall. Figure 4.26 shows selected skew-T diagrams of Hurricanes Katrina and Rita from the MM5 output from 1900-2000 UTC August 28 for Katrina and 1100 UTC September 22 for Rita. The soundings from Hurricane Rita (shown in panels c and d), demonstrate a nearly saturated lower troposphere, with a drying at around 800mb. Since this is similar to the observations, the MM5 can be used to study the evolution of the moat area in Katrina and Rita and its affect on the rainbands.
The main difference between Katrina and Rita in the moat region is the depth of the dry layer. If one were only to examine the same vertical domain as sampled by the

Figure 4.25: Skew-T diagram from an NRL dropsonde deployed in the moat of Hurricane Rita at 1801 UTC, September 22, 2005. Red line is the temperature and blue line is the dewpoint.

Figure 4.26: Skew-T diagrams of Hurricanes Katrina (a and b) and Rita (c and d) from the MM5 output at 0800 UTC August 28, 2005 for Katrina and 1100 UTC September 22 for Rita. The red line is the temperature and the blue line is the dewpoint. The soundings were taken from the moat of Rita and from the moat like area of Katrina.
dropsondes, one could conclude that the moat regions are similar, with drying above 800mb. However, in Rita, the troposphere is dry above this region. In contrast the troposphere in Katrina is saturated above the 600-500mb level. This suggests that a true moat is characterized by a deep dry layer throughout the troposphere. A false moat may only involve drying over a shallow layer. Observations from Hurricane Rita on September 22 confirm the deep layer of descending motion (Houze et al., 2007). Doppler radar within the moat region of Rita shows a deep layer of depressed dBZ values in comparison to the eyewall. This is likely due to the convective circulations associated with the primary and secondary eyewalls. Divergence occurs at the top of both eyewalls, leading to convergence over the moat region, requiring descending motion due to the conservation of mass.

The MM5 output shows features that are very similar to those depicted in the observations. Figure 4.27 shows four east to west cross sections of Rita from September 22, showing the MM5 dBZ, along with the radial and vertical winds. At 0000 UTC, shown in panel (a), Rita had a well-defined primary eyewall, with very strong upward vertical motion and dBZ values between 40 and 50 in the lower troposphere. The dBZ decreased to about values of 30 to 40 aloft. In addition, a secondary eyewall was present, though at this time it was weaker than the primary eyewall as shown by dBZ and updraft velocities lower than those of the primary eyewall. Between the two eyewalls, dBZ values are at or below 0 in the lower troposphere, increasing to 20 dBZ in the upper troposphere. There is not a well-defined deep layered descending motion at this time. Six hours later, shown in panel (b), descending motion due to the vertical circulations associated with the eyewalls begins to establish itself between the two eyewalls. The
descending motion at this time is restricted to heights greater than 8km. This causes the upper troposphere to dry and dBZ values to lower, approaching 0 between 8-12km. The updrafts in the primary eyewall are now restricted to the lowest 10km, whereas they extended to 14km just six hours before. The secondary eyewall becomes the stronger eyewall at 1100 UTC, shown in panel (c). Updrafts now extend in the secondary eyewall to similar heights as in the primary eyewall at 0000 UTC. Descent is present in the moat and over the primary eyewall at heights as low as 6km. In the moat region, there is now a large area is negative dBZ values above 8km between the two eyewalls, with a tongue of these low values extending to about 6km. The primary eyewall completely dissipated by 2100 UTC, shown in panel (d), leaving a single outer eyewall about 25km from the center of the eye. This outer eyewall is very similar to the original eyewall 21 hours earlier. Inside, typical eye characteristics are present with deep layered descent and negligible dBZ. The descending motion did not spread over the secondary eyewall. Instead, upward motion continued throughout the eyewall replacement. A possible reason for this is that the outer eyewall continued to receive low-level inflow, while the outer eyewall blocked the inflow from reaching the primary eyewall. This would serve to allow convective activity to continue in the secondary eyewall, while reducing it in the primary eyewall. The result would then be a reduction in the updrafts in the primary eyewall, while they would be maintained within the primary eyewall. This could allow the descending motion to spread over the primary eyewall, but prevent it from spreading over the secondary eyewall.

Hurricane Katrina, in contrast, does not have these well-defined characteristics within its moat-like region. The eyewall and rainbands are weaker than those of Rita in
terms of dBZ. Figure 4.27 shows MM5 cross sections of Katrina at selected times from August 28. At 0600 UTC, shown in panel (a), Katrina has a single eyewall, with rainbands outside. Between the bands, there is an area of low dBZ. However, there was no descending motion. Instead, ascent occurred in the lower portions of the troposphere. Furthermore, the rainbands near 35 and 60km have updrafts that only reaches about 3-4km, below that of the primary eyewall, as well as the secondary eyewall of Rita. Model dBZ values are also lower throughout the depth of the rainband than those from Rita. This comparative weakness of Katrina's rainbands persists through the time period presented here. At 1200 UTC, shown in panel (b), the primary eyewall intensifies as evidenced by the increased vertical velocities. However, there again is no large scale descent within the area between the eyewall and rainband now at 40km. In fact, just outside of the eyewall, there is a hint of a band between the eye and rainband with high circularity. At 1800 UTC, shown in panel (c) the eyewall at about 20km again is the most intense feature in terms of dBZ and vertical velocity and there continues to be a lack of descent between the eyewall and outer rainband, which has weakened. At 0000 UTC August 29, shown in panel (d), the eyewall is even more dominant as updrafts far exceed those of the outer band. There also continues to be no significant descending motion within the "moat" area.

The results presented above demonstrate that the main difference between Katrina and Rita within the moat region is the lack of descending motion present in Katrina between the eyewall and outer rainbands. This lack of descent prevented a true moat to form. The lack of a persistent rainband with high circularity, demonstrated in section 4.4 may be responsible. This, there was not the deep layered descent for a prolonged period
of time over the primary eyewall of Katrina. This descent appears to be the cause of the weakening of the primary eyewall when there is a persistent circular rainband present. This lack of descent allowed the primary eyewall of Katrina was able to maintain its intensity.

Figure 4.27: MM5 dBZ and radial/vertical wind cross sections of Hurricane Rita from September 22, 2005 at 0000 UTC (a), 0600 UTC (b), 1100 UTC (c), and 2100 UTC (d).
Figure 4.27 continued
Figure 4.28: Same as Fig 4.27, except for Hurricane Katrina on August 28, 2005 at 0000 UTC (a), 0600 UTC (b), 1200 UTC (c), and 1900 UTC (d).
Figure 4.28 continued.
4.6 Summary

Hurricanes Katrina and Rita exhibited very different rainband patterns and environmental water vapor distributions. Hurricane Katrina was located within a moist environment. This allowed for there to be a weak moisture gradient between the hurricane and outer environment. The rainbands of Katrina had low circularity. Rita was located within a dry environment. A sharp moisture gradient was present between the hurricane and outer environment. The rainbands had high circularity, which eventually formed into a secondary eyewall.

It is believed that the water vapor distribution was responsible for the rainband patterns. A possible mechanism was through the atmospheric stability in the outer environments. The moist outer environment that Katrina was located within was unstable, allowing for rainbands to be located farther from the eye. The dry outer environment that Rita was in was stable. This confined the rainbands closer to the storm. The wind circulation around Rita allowed for the rainbands to have high circularity. These outer rainbands eventually led to the formation of a moat region between the rainband and eyewall. Within this moat region was strong descending motion throughout the troposphere. The descending motion eventually spread over the eyewall, leading to its destruction and eventual replacement by the developing secondary eyewall.
Chapter 5: Conclusions and Future Work

5.1: Summary and Conclusions

Mechanisms through which environmental water vapor affects TC structure and intensity were reviewed and evaluated. Through a statistical analysis using SSM/I TPW and GPS dropsonde data, it was demonstrated that TC intensification is more likely to occur in environments where there is above average moisture. Dry air can result in the weakening of a TC, especially in the presence of a relatively strong vertical wind shear. It was hypothesized that strong shear allows the dry air to penetrate into the inner core region of the TC. When dry air penetrated the inner core, weakening, sometimes rapid weakening, may occur. When vertical wind shear was low, dry air tended to remain outside of the TC inner core, allowing the TC to maintain its intensity in many cases.

The RAINEX observations and high-resolution model forecast fields provided a unique glimpse of the impacts of environmental water vapor on TC rainband structure and intensity in Hurricanes Katrina and Rita. TRMM TMI, GPS dropsondes, and MM5 output demonstrated that Katrina was located within an anomalously moist outer storm environment, when compared with the 1998-2005 composite mean presented in chapter 3. The moisture gradient between the rainbands and the outer environment was weak. This moist outer environment was unstable and favored convective activity. Rita, in contrast, featured an anomalously dry outer environment. The dry air primarily confined to the middle levels of the troposphere; specifically, between 5 and 8km. An index, the MSI, measuring atmospheric stability due to the dry air is well correlated with convection...
in the observations and model output, suggesting that it is a good measure of stability for this study.

The rainband patterns of the two storms were significantly different. Using the circularity index of the fractional coverage of rainrate greater than 12.5mm/h at any particular radius, it was demonstrated that Katrina’s rainbands exhibited little circularity, with no secondary eyewall candidates. Hurricane Rita had rainbands with high circularity. Two rainbands outside of the eyewall were candidates for a secondary eyewall, with circularity greater than .5. The aircraft and model flight level data verified that one of these bands was an outer eyewall. The rainbands outside of the secondary eyewall had more than twice the circularity of those from Katrina.

Atmospheric stability appears to be a mechanism through which the environmental water vapor impacts the development of the rainbands. Within the moist areas, the MSI depicted an unstable environment, while in the dry regions, the MSI showed a highly stable environment. The MSI 10K radius was critical for rainband formation. The large outer rainbands with high circularity were confined to within this radius, with all significant convective activity within the MSI 2.5K radius. In the case of Rita, the MSI 10K radius was near the wind circulation of the TC. This allowed for the developed rainbands to have high circularity. In Katrina, the MSI 10K radius was well outside of the wind circulation, allowing for the rainbands to have lower circularity than those of Rita. These results are summarized in Fig 5.1 as a conceptual model of the impacts of environmental water vapor on TC rainband structure. The left half has a weak, radial moisture gradient with the outer environment, represented by the area outside of the rainbands, moist and unstable. The right half has a strong, radial moisture gradient
with dry and stable air much closer to the center than in the left half. In the sharp gradient case, the rainbands are confined near the center, promoting a pattern of increased circularity of the rainbands. These rainbands then propagate in toward the eyewall. In the weak gradient case, the rainbands have lower circularity and extend farther from the center. These rainbands do not form into a secondary eyewall.

Figure 5.1: Conceptual model of moisture gradient and TC rainband structures. Relatively weak gradient (left) may favor for extended spiraling rainbands as in the case of Katrina, whereas a strong moisture gradient may be a factor that confining the rainbands at the radius where the strong gradient is. Areas inside of the red circle represent very moist and unstable environment while areas outside of the light blue represent dry and stable. The teal shapes represent the TC rainbands.

5.2. Future Work

Observations and MM5 output show a clear link between environmental water vapor and TC structure and intensity. There is shear dependence to this link as vertical shear may allow for dry air to penetrate the core, causing weakening. It was also
hypothesized that dry environmental air can affect the rainband structure in low shear environments. This hypothesis can be furthered refined by a multi step approach, using additional numerical model and observational studies.

First, model sensitivity tests could be performed, similar to the one by Lonfat (2004), which addressed the impact of water vapor on TC rainbands. This study would be similar in that it would make adjustments to the water vapor field, though only the environmental water vapor would be adjusted. The possible sensitivity test would involve three sets of idealized simulations, using identical SST, initial vortex from the Hurricane Rita simulation, and environmental conditions, with the exception of environmental water vapor. All effects of land would be removed. The SST would be set at a uniform 303K, similar to the SST in the Gulf of Mexico during Katrina and Rita. The vertical shear would be consistent with the low values experienced by the two storms. The vortex would be the initial Rita vortex since it had circular bands and underwent an eyewall replacement, allowing for the effects of the moisture distribution to be isolated.

Simulation set 1 (Simulation 1) would feature the same environmental moisture as Hurricane Katrina. It is expected that if the water vapor distribution is the critical parameter to determining the rainband distributions the initial Rita vortex would evolve in a manner more consistent with Katrina than Rita, in terms of its rainband pattern and structure. Simulation set 2 (Simulation 2) would feature a dry outer storm environment, similar to that observed in Hurricane Rita and this vortex would be expected to evolve similar to the initial Rita forecast.

After quantifying the differences between Simulation 1 and 2, further simulations within Simulation 2 would be conducted. Specifically, the radius of the dry environment
will be varied. The purpose of varying this radius is to determine if there is a critical
radius at which the dry air causes the rainbands with high circularity and eyewall
replacement. If it is determined that there is a critical radius present, an additional
simulation will be conducted. This additional simulation would consist of reducing the
moisture content within the hurricane itself. The purpose of this is to test whether it is the
moisture gradient is the cause of the rainbands having high circularity, or the dry stable
environment. The reason that this additional test is due to some results from Hurricane
Frances. Figure 5.2 shows a TRMM TMI TPW pass for Hurricane Frances from 1021
UTC August 30, 2004, along with corresponding 85 GHz image showing the rainband
patterns from the same time as the TPW pass. The circulation of Hurricane Frances had
lower TPW content than did the circulation of Hurricane Rita (refer to Fig 4.4). The outer
environmental TPW was similar to that of Rita. The composite RH profiles (not shown)
from the G-IV aircraft also showed a similar signal as in the Rita case. This hints that it
may be the dry stable air itself, and not the gradient of the water vapor, that affects the
rainband distribution. The sensitivity test would answer this question.

The model sensitivity test will advance to the third and final phase if Simulation 2
demonstrates a critical radius at which the environmental water vapor affects TC
rainband structure and distribution. This third and final phase, Simulation 3, will involve
making modifications to the initial vortex. The purpose of this is to determine how
variations in the initial vortex structure would affect the impacts of the environmental
water vapor on the rainbands. Chen (2006) demonstrated that a larger initial vortex in
Rita resulted in the vortex evolving in a manner similar to Isabel from 2003 (Beven and
Cobb, 2003), with a very large eye. TCs with a larger eye may be less prone to circular
rainbands and eyewall replacement than those with small eyes. Hurricane Katrina on August 26 and early on August 27 of 2005 (Knabb et al. 2006) had a very small eye of about 10km in diameter and underwent an

Figure 5.2: TRMM TMI water vapor image (a) and 85 GHz (b) for Hurricane Frances from 1021 UTC, August 30, 2004.
eyewall replacement. This occurred despite a relatively moist environment, shown in Fig 5.3, which shows the composite RH profile from the G-IV dropsondes. Simulation 3 will feature increasing and decreasing the size of the initial vortex, along with the environmental water vapor distribution. The goal of this is to quantify, possibly in the form of a mathematical function, of the combined effects of the initial vortex and the water vapor distributions, which would make prediction of the rainband structures, and possibly eyewall replacements possible in real time, assuming that the correct environmental water vapor and initial vortex size is available from in situ or numerical modeling simulations.

Figure 5.3: Composite environmental RH profile from G-IV dropsondes for Hurricane Katrina from August 26, 2005.

The results of the model sensitivity test would then be compared with observations to determine their applicability in real TCs. This observational study would include using TRMM TMI water vapor and rainrate data from around the world from
1998 through 2006-2007, in both the northern and southern hemisphere. Systems that reached the equivalent of category 3 intensity according to the official World Meteorological Society (WMO) best track data (with the appropriate corrections applied to all basins, except the Atlantic and the North Pacific east of 180W, to convert from 10 minute to 1 minute sustained winds) would be candidates for study. TMI passes would be retained when there is complete coverage of the TC. The rainband patterns would be quantified in the same manner used in this thesis. TCs would be separated into two groups. The first would contain rainbands other than the eyewall with a circularity greater than 50 percent and the second without. The environmental water vapor distribution would then be quantified using the TMI water vapor data for all TCs and GPS dropsondes for certain Atlantic TCs. The differences between the environmental water vapor and eye sizes would be closely evaluated. The goal would be to provide insight regarding how observed TCs react to differences in vortex size and water vapor with regards to their rainband patterns and whether these two factors are critical to eyewall replacement in all TCs.

A second line of future work would center on evaluating the VRW activity within Hurricanes Katrina and Rita. It has been established that TC rainbands are affected by VRW activity (e.g. Montgomery and Kallenbach 1997, Schubert et al. 1999, Kossin et al. 2000, Chen and Yao 2001, Wang 2002, Chen and Yao 2003, Corbosiero et al. 2006). Analysis is currently being conducted to determine how the rainbands of Katrina and Rita were affected by VRW activity. This topic could focus upon how the large scale water vapor distribution and the VRW interact to determine TC rainband structure. Specifically, the question of whether or not secondary eyewall formation is affected by VRW activity,
as is suggested in the papers cited above, can be answered. This line of work would advance the science as the environmental impacts would be considered. The studies above did not consider environmental controls on rainband formation. This work would determine, whether the environmental moisture distribution or VRW activity has the greater affect on outer rainband and secondary eyewall formation.
References:


