Convectively-Generated Potential Vorticity in Rainbands and Secondary Eyewall Formation in Hurricanes

Falko Judt

University of Miami, fjudt@rsmas.miami.edu

Follow this and additional works at: https://scholarlyrepository.miami.edu/oa_theses

Recommended Citation
https://scholarlyrepository.miami.edu/oa_theses/214
CONVECTIVELY-GENERATED POTENTIAL VORTICITY IN RAINBANDS AND SECONDARY EYEWALL FORMATION IN HURRICANES

By

Falko Judt

A THESIS

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements for
the degree of Master of Science

Coral Gables, Florida

June 2009
UNIVERSITY OF MIAMI

A thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Science

CONVECTIVELY-GENERATED POTENTIAL VORTICITY IN RAINBANDS AND
SECONDARY EYEWALL FORMATION IN HURRICANES

Falko Judt

Approved:

Shuyi Chen, Ph.D.
Professor of Meteorology

Terri A. Scandura, Ph.D.
Dean of the Graduate School

Benjamin Kirtman, Ph.D.
Professor of Meteorology

Robert Houze, Ph.D.
Professor of Meteorology
University of Washington
Seattle, Washington
Concentric eyewall formation and eyewall replacement cycles are intrinsic processes that determine the intensity of a tropical cyclone, as opposed to purely environmental factors such as wind shear or the ocean heat content. Although extensive research has been done in this area, there is not a single widely accepted theory on the formation of secondary eyewall structures. Many previous studies focused on dynamic processes in the inner core of a tropical cyclone that would precede and ultimately lead to the formation of a secondary eyewall.

Hurricanes Katrina and Rita in 2005 were frequently sampled by research aircraft which gathered a copious amount of data. During this time, Rita developed a secondary eyewall which eventually replaced the original eyewall. This thesis will investigate the formation of a secondary eyewall with particular emphasis on the rainband region, as observations show that and outer principal rainband transformed into the secondary ring. A high resolution, full physics model (MM5) initialized with global model forecast fields correctly predicted the secondary eyewall formation in Rita. The model output will be used to investigate both Katrina and Rita in terms of their PV generation characteristics since PV and vorticity maxima correlate well with wind maxima that accompany the
eyewall and rainbands. Furthermore, dynamical processes such as vortex Rossby wave (VRW) activity in the inner core region will be analyzed. Comparison of the differences in the two storms might shed some light on dynamics that can lead to structure changes.

Comparison of the model data with aircraft observation is used to validate the results. Doppler radar derived wind fields will be used to calculate the vertical vorticity. The vorticity field is closely related to PV and thus a manifestation of the PV generation process in the rainband. The investigation has shown that Rita’s principal rainband features higher PV generation rates at radii beyond 80 km. Both the azimuthal component and the projection of asymmetric PV generated by convection onto the azimuthal mean connected with the principal band are hypothesized to be of importance for the formation of the secondary eyewall. VRW were found not to be important for the initial formation of the ring but might enhance convective activity once the outer eyewall contracts.
ACKNOWLEDGEMENTS

I want to sincerely thank my advisor Dr. Shuyi Chen for her guidance and encouragement. I also want to thank my committee members, Dr. Robert Houze and Dr. Ben Kirtman, for their insight into this work and valuable comments. Furthermore, I would like to offer my gratitude to Dr. Wei Zhao for his assistance in running the MM5 simulations and Dr. John Gamache (NOAA/AOML/HRD) for providing help with processing the Doppler radar data.
# TABLE OF CONTENTS

**LIST OF FIGURES** ................................................................. vi

**Chapter**

1 **INTRODUCTION** ................................................................. 1
   1.1 An overview ..................................................................... 1
   1.2 Motivation ...................................................................... 4
   1.3 Background and literature review ...................................... 6
       1.3.1 Hurricane rainbands ............................................. 6
       1.3.2 Inner core dynamics and eyewall replacement cycles .... 11
   1.4 Science objectives and working hypothesis ......................... 16
   1.5 Outline ........................................................................... 17

2 **METHODOLOGY** ................................................................. 19
   2.1 The numerical model ...................................................... 19
   2.2 Observational datasets ................................................... 21
       2.2.1 Aircraft observations during the RAINEX field program ... 21
       2.2.2 Satellite data ......................................................... 23

3 **SYMMETRIC STRUCTURE OF HURRICANES RITA**
   AND KATRINA (2005) ............................................................. 24
   3.1 Synopsis ......................................................................... 24
       3.1.1 Hurricane Katrina ................................................. 24
       3.1.2 Hurricane Rita ...................................................... 29
   3.2 Model forecasts and verification ........................................ 32
       3.2.1 Track and intensity .................................................. 32
       3.2.2 Storm structure from the model and observations ......... 36
   3.3 Evolution of the symmetric structure .................................. 43
       3.3.1 Potential vorticity (PV) distribution ......................... 43
       3.3.2 Evolution of rain, wind and PV .............................. 50
   3.4 Vortex Rossby waves ...................................................... 55
       3.4.1 Distinct features in Katrina and Rita ......................... 55
       3.4.2 Effects of VRW on storm evolution ......................... 63

4 **SECONDARY EYEWALL FORMATION IN RITA** ..................... 73
   4.1 PV generation and redistribution ..................................... 73
       4.1.1 PV budget equation .............................................. 74
       4.1.2 PV budget of the inner core .................................. 76
       4.1.3 PV budget of the rainband region ......................... 82
       4.1.4 Secondary PV maximum and secondary eyewall formation .... 86
**LIST OF FIGURES**

1.1 (a) WSR-88D radar image of Hurricane Rita. (b) MM5 model rain rate of Katrina (in mm hr\(^{-1}\)).......................................................... 8

1.2 Model instantaneous rain rates (in mm hr\(^{-1}\)) of (a) Katrina at 0848 UTC 28 August and (b) Rita at 2212 UTC 21 September 2005................................. 10

2.1 Example of multi-nested MM5 domains with 15, 5, 1.67 km grid resolutions, respectively. The inner domains are vortex following nests that can be initialized at a location of a storm..................................................... 21

3.1 Intensity evolution of Hurricane Katrina from National Hurricane Center (NHC) best track data. Blue is maximum surface wind speed, green minimum sea level pressure. Arrows indicate RAINEX flights into the storm...................... 25

3.2 Rainrate estimated from TRMM TMI (in inch hr\(^{-1}\)) for Katrina at (a) 2148 UTC 26 August 2005, (b) 2052 UTC 27 August 2005. Red circles indicate the eyewall at the respective times. From Navy NRL Tropical Cyclone Page [http://www.nrlmry.navy.mil/tc_pages/tc_home.html]......................... 28

3.3 Same as Fig. 3.1, but for Rita. Arrows indicate RAINEX flights into Rita, the dashed arrow marks a joint RAINEX-NHC mission. The red shading indicates the time Rita underwent the EWRC.................................................. 29

3.4 Storm tracks from MM5 forecasts (blue) and the NHC best track data (black) of (a) Hurricane Katrina from 0000 UTC 27-30 August 2005 and (b) Hurricane Rita from 0000 UTC 20-25 September 2005........................................ 32
3.5 Maximum surface wind speed from MM5 forecasts (blue) and the NHC best track data (black) in (a) Hurricane Katrina from 0000 UTC 27-30 August 2005 and (b) Hurricane Rita from 0000 UTC 21-25 September 2005.

3.6 Time-radius (Hovmöller) diagram of wind speed (in m s$^{-1}$) at 700 mb in (a) Katrina from 1200 UTC August 27 – 1200 UTC 29 August, (b) in Rita from 0000 UTC 21 September – 0000 UTC 23 September.

3.7 Comparison of vertical vorticity at the 700 mb level from (a) aircraft Doppler radar observations and (b) MM5. For the observed vorticity, two flight legs through the storm center have been composited (between 1506 and 1617 UTC 21 September 2005), (b) is a snapshot from 1800 UTC 21 September 2005.

3.8 Same as Fig. 3.7, but for (a) 1435 – 1638 UTC 22 September 2005 and (b) 1048 UTC 22 September 2005.

3.9 Same as Fig. 3.7, but for (a) 1702 – 1818 UTC 22 September 2005 and (b) 1112 UTC 22 September 2005.

3.10 Same as Fig. 3.7, but for (a) 1856 – 2100 UTC 22 September 2005 and (b) 1300 UTC 22 September 2005.

3.11 Same as Fig. 3.7, but for (a) 1640 – 1802 UTC 23 September 2005 and (b) 1000 UTC 23 September 2005.

3.12 (a) Azimuthally and 1-hourly averaged PV (solid) and vertical vorticity (dashed) at 700 mb from the model for Katrina at 0300-0400 UTC and 1900-2000 UTC 28 August. (b) Same as (a) but enlarged ordinate.

3.13 Azim. averaged PV (colors, displayed in log-scale) and wind speed (contours, in m s$^{-1}$) at 700 mb. Data from MM5; (a) Katrina, (b) Rita.
3.14 Time-radius diagram of azim.-aver. PV (colors, in m² s⁻¹ K kg⁻¹) and wind speed (contours, in m s⁻¹) at 700 mb in (a) Katrina and (b) Rita………………….. 49

3.15 Azimuthally averaged PV (red), rain rate (blue) and wind speed (black) from MM5 in Katrina. Each panel represents an average over 1 hour, centered on the time given in the title of each panel…………………………………………………………. 51

3.16 Same as Fig. 3.15, but for Rita…………………………………………………………… 54

3.17 Wavenumber 2 components of PV (colours, in m² s⁻¹ K kg⁻¹) and vertical velocity (contours). (b) Wavenumber 1 components of rain rate (colors, in mm hr⁻¹) and PV (contours). Cross-sections to the east of the storm center at 700 mb (rainrate at the surface)……………………………………………………………………………………… 56

3.18 Same as Fig. 3.17, except for wavenumber 3 components…………………. 58

3.19 (a) Wavenumber 1 components of rain rate (colors, in mm hr⁻¹) and PV (contours) in Rita, (b) same as (a) but for Katrina…………………………………………………………… 59

3.20 Same as Fig. 3.19, except for wavenumber 2 components…………………. 60

3.21 Same as Fig. 3.19, except for wavenumber 3 components…………………. 61

3.22 Same as Fig. 3.19, except for wavenumber 4 components…………………. 62

3.23 (a) Fractional coverage of rain rate > 12.5 mm hr⁻¹ (colors) and wavenumber 1 component of PV (contours, cross sections to the east of storm center) in Katrina. (b) same as (a) except for wavenumber 2 component……………………………. 64

3.24 Same as Fig. 3.23 except for (a) wavenumber 3 component and (b) wavenumber 4 component…………………………………………………………………………… 66
3.25 (a) Fractional coverage of rain rate > 12.5 mm hr⁻¹ (colors) and wavenumber 1 component of PV (contours, cross sections to the east of storm center) in Rita. (b) same as (a) except for wavenumber 2 component 68

3.26 Same as Fig. 3.25 except for (a) wavenumber 3 and (b) wavenumber 4 components 69

3.27 Eddy momentum flux divergence (blue) and azimuthally-averaged tangential wind speed (green, not to scale) at 700 mb in Katrina. Averaged over the time period 0300-0900 UTC 28 August 71

3.28 Same as Fig. 3.27, but for Rita. Averaged from 0000-0600 UTC 22 September 72

4.1 Horizontal cross sections of (a) PV and (b) rain rate in Rita. Black lines denote inner core and rainband region 76

4.2 The rate of PV generation (solid colored lines) at 700-mb level due to the azimuthally averaged (mean) diabatic heating (a) and the perturbation diabatic heating (b). Blue is Katrina, red is Rita. The rain rates are shown in dashed lines for Katrina (blue), Rita (red), and averaged PV in black (solid Rita, dashed Katrina). The variables are 6-hour averages from 0300-0900 UTC on 28 August 2005 for Katrina and 0800-1400 UTC on 21 September 2005 for Rita 78

4.3 Same as Fig. 4.2, but from 1000-1600 UTC in Katrina and 1500-2100 UTC in Rita 79

4.4 Same as Fig. 4.2, but from 1300-1900 UTC in Katrina and 0000-0600 UTC 22 September in Rita 80
4.5 Same as Fig. 4.2, but from 1300-1900 UTC in Katrina and 1200-1800 UTC in Rita. 

4.6 The rate of PV generation (solid colored lines) at 700-mb level due to the azimuthally averaged (mean) diabatic heating (a) and the perturbation diabatic heating (b). Blue is Katrina, red is Rita. The rain rates are shown in dashed lines for Katrina (blue), Rita (red), and averaged PV in black (solid Rita, dashed Katrina). The variables are 6-hour averages from 0300-0900 UTC on 28 August 2005 for Katrina and 0800-1400 UTC on 21 September 2005 for Rita. 

4.7 Same as Fig. 4.6, but from 1000-1600 UTC in Katrina and 1500-2100 UTC in Rita. 

4.8 Same as Fig. 4.6, but from 1300-1900 UTC in Katrina and 0000-0600 UTC in Rita. 

4.9 Difference of PV generation rates (blue: perturbation diabatic heating, red: mean diabatic heating), azimuthally averaged PV (solid black) and rain rate (dashed black) between Rita and Katrina. Positive values denote larger values in Rita. Averaged from 0300-0900 August 28 in Katrina and 0800-1400 UTC September 21 in Rita. 

4.10 Same as Fig. 4.9, except for averages from 1000-1600 UTC in Katrina and 1500-2100 UTC in Rita. 

4.11 Same as Fig. 4.9, except for averages from 1300-1900 UTC in Katrina and 0000-0600 UTC September 22 in Rita. 

5.1 Schematic of radial distribution of PV generation rates in Katrina (blue) and Rita (red).
Chapter 1

Introduction

1.1 An overview

Tropical cyclones (TCs) are fast rotating atmospheric vortices that form over the warm tropical oceans. They can grow into powerful storms with winds exceeding 70-80 m s\(^{-1}\) and are one of the most destructive natural phenomena both in terms of loss of life and economic impact when making landfall (e.g., Pielke and Landsea 1996, Cutter et al. 2003, McPhaden 2009). In order to better prepare and ultimately mitigate the impacts of TCs, intensity forecasting of such storms is of major importance. While improvements have been made in predicting the tracks of TCs over the last a few decades (Franklin et al. 2003), the prediction of a TC’s intensity remains a challenge. It became apparent that a better understanding of the physical processes that determine the structure and intensity of a TC is needed for making improvements in the intensity forecasting. A TC is an atmospheric system in which latent heat is released in convective scale elements and its effects “transferred” upscale. The energy cascades through mesoscale convective features like the eyewall and rainbands and ultimately drives the pressure and the mean vortex wind field of the cyclone. Because of the importance of small scale convective elements, numerical simulations yield better results when high-resolution models are used which can resolve these small scale features explicitly (e.g. Chen et al. 2007). On the other hand, the large-scale environmental conditions play an important role in TCs intensity by interacting with TCs during its life time. The general underlying physical processes determining the structure and intensity of TCs were found to be twofold:
1) State of the TC environment. For example, the warm ocean provides the energy to drive the cyclone, the large-scale atmospheric conditions such as vertical wind shear or the abundance (or lack) of atmospheric moisture can pose a powerful constraint on the intensity of a TC.

2) TC internal dynamical processes. Recently, especially with the advancement of observations and high-resolution numerical models, substantial progress has been made in understanding how these intrinsic dynamics contribute to storm structure and intensity.

Even though both paradigms contributing to intensity changes in TCs have been addressed extensively, the interaction between the outer region of a storm and intrinsic inner core processes have been largely neglected so far. It is believed that the outer regions of a storm are largely influenced by large-scale environmental conditions such as vertical wind shear (e.g. Black et al. 2002, Rogers et al. 2003, Chen et al. 2006) and moisture distributions that could affect the storm structure (e.g. Ortt and Chen 2008).

Two recent research programs designed to better understand effects of the air-sea interaction (the Coupled Boundary Layer Air-Sea Transfer (CBLAST) - Hurricane) and the rainband and TC dynamics (the Rainband and Hurricane Intensity Change Experiment-RAINEX) on intensity have added some new knowledge. The research community is now able to understand reasonably well the governing processes of dynamic features in the inner core. The reason why most TCs do not reach their maximum potential intensity (MPI, which is a thermodynamic constraint on intensity posed by environmental conditions) is due to hostile atmospheric environmental conditions such as strong wind shear or dry, stable air in the vicinity being entrained into
the system. But even if these unfavorable factors were absent, TCs seldom reach their MPI or undergo intensity fluctuations even though the environmental factors are unaltered. These intensity changes can be linked to transitions in the storm’s structure. A frequently observed structural process in mature TC is the formation of a secondary eyewall. A secondary (or outer) eyewall forms from an outer concentric ring of convection. In many storms the outer eyewall develops when a large rainband, which usually has a spiral shape, wraps around the inner core and coalesces with other rainbands so that in an azimuthally averaged sense a secondary ring of convection forms. It should be noted that the mere existence of a secondary ring of convection is not enough for being called a secondary eyewall, but a wind maximum in the symmetric (azimuthally-averaged) wind field must be prevalent. In terms of intensity, the formation of a secondary eyewall usually decreases the storm’s intensity. The inner (original) eyewall weakens once the secondary eyewall becomes more established due to decreased energy fluxes in the inflow layer which are taken up by the outer eyewall. However, the wind maxima connected with the outer eyewall are usually weaker than the primary eyewall wind maxima but can strengthen with time when the new eyewall contracts. In this case, the storm can become as powerful or even stronger as it was before the formation of the new eyewall. This process can repeat itself several times during the life cycle of a TC and is called eyewall replacement cycle (EWRC).
1.2 Motivation

Although extensive research has been conducted on the secondary eyewalls in the recent years, especially theoretical and simple modeling studies, there is no clear explanation on the formation of concentric eyewalls in TC. In order to develop more skillful intensity forecasting techniques, it is important to be able to understand and predict the formation of secondary eyewalls.

In this study, we focus on trying to better understand the physical and dynamical processes that lead to formation of secondary eyewalls. In particular, we will analyze two Atlantic hurricanes, Katrina and Rita (2005), which were well-observed and modeled during RAINEX (Houze et al. 2006, 2007). They were both major category 5 storms over the Gulf of Mexico. Hurricane Rita underwent a EWRC, whereas Katrina did not. The question is what is the difference in the structure of rainbands and inner-core dynamics of the two storms? And are these differences important for the formation of secondary eyewalls? We will examine the mean vortex PV distribution and convectively-generated PV in the rainbands of the two hurricanes. The results may help us to understand the role of PV generation by moist convection in the rainband region on the formation of secondary vorticity and wind maxima, which lead to the development of concentric eyewall and EWRC.

Previous studies on concentric eyewalls either used simplified dry dynamical models or full-physics models with prescribed and idealized environmental conditions. Dry models do not have the ability to account for generation of PV through latent heat release. Several studies found however that persistent rainbands and secondary eyewall structures are always linked to wind and vorticity maxima (Hence and Houze 2008,
hereafter HH08) which are believed to be generated by convection and/or stratiform precipitation (e.g. May and Holland 1999, Franklin et al. 2006). Even though later studies made use of full-physics high-resolution models in order to understand the development of secondary eyewalls, interactions with a TC’s environment are excluded due to idealized and prescribed initial and boundary conditions. In this study, we use high-resolution full physics model forecasts of real hurricanes so that we can understand interactions between a hurricane’s inner core and outer rainbands, which may be important for EWRC to occur. Observations of the outer vorticity fields show distinct differences in Katrina and Rita indicating convectively-generated PV in rainbands may play a role in the evolution of the two storms. We examine how convectively-generated PV alters the azimuthally-averaged radial PV gradient, which itself is a key factor for dynamic processes. What impact does this have on the formation of concentric eyewalls? Previous idealized modeling studies have focused on inner rainbands as precursors for concentric rings of convection. However, we will show that it is clearly an outer rainband originating far from the center of Hurricane Rita that forms into the secondary eyewall. It is thus important to focus not only on the inner core the hurricane but also on factors influencing the structure and evolution of the outer rainband region and their interactions with the inner core.
1.3 Background and literature review

1.3.1 Hurricane rainbands

Since the advent of radar-equipped reconnaissance aircraft flying into hurricanes, meteorologists are aware of the general TC structure. It was indentified that mature hurricanes usually have a precipitation free, relatively calm eye surrounded by the eyewall exhibiting intense convection and the strongest winds. Either connected to or separated from the eyewall, rainbands of spiral shape are embedded in the cyclonic flow. These rainbands consist of heavy convection and large areas covered by stratiform precipitation. Houze (2009) gives a comprehensive overview of the current state of rainband diversity and terminology. Willoughby (1984) was probably the first to comprehensively describe the nature of rainbands as he distinguished between moving and stationary rainbands. He found that most hurricanes exhibit similar rainband structures as far as the stationary bands are concerned. Willoughby called this feature the “stationary band complex (SBC)”. The most notable characteristic of the SBC is the “principal band”, a long rainband stretching from the immediate inner core to the outer regions of a hurricane. Due to its size it can wrap around half the cyclone and constitutes a wavenumber 1 asymmetry in the precipitation. This feature is reminiscent of the genesis stage of a TC which is dominated by a wavenumber one asymmetry in convection and wind speed but can also be related to other factors usually connected with a wavenumber 1 asymmetry such as vertical wind shear and relative motion (DeMaria 1996, Chen et al. 2006). Willoughby also identified smaller rainbands which were more transient in nature and moved with respect to the center. Those bands were called “secondary rainbands”.
Later studies added to this approach and focused not only on the temporal evolution, i.e. moving or stationary, but on the governing dynamics (Houze 2009). It became apparent that rainbands in the inner regions of a mature hurricane are heavily constrained by the strong swirling winds and outflow from the eyewall. The strong differential rotation in the inner core leads to a process called filamentation where convective features are becoming elongated and thinner with time due to the shearing deformation. Rozoff et al. (2006) developed a filamentation time scale and hypothesized that the rapid filamentation zone of a hurricane does not promote convection at all because of the intense shearing strain an air parcel would be subject to. They concluded that in this area where the filamentation time scale is smaller than the convective time scale rainbands will not be found. In a following study (Wang 2008) rejected this hypothesis and showed that even in regions with intense shearing deformation convection can organize into rainbands with temporal time scales of a few hours. This is also evidenced by radar observation where rainbands with radial scales of ~10 km are readily identified in the inner core. Constrained in the vertical by the outflow from the eyewall, the principal and secondary bands are usually shallower than the eyewall and convection that occurs farther away from the center. Tangential winds decrease with radius so that the dynamical constrains imposed on convecting particles by the rapidly rotating vortex becomes less important. This means that convection in the “distant or outer rainbands” is mainly governed by factors also found in regular squall lines. Buoyancy driven updrafts and downdrafts contribute to a cellular appearance on radar imagery and they can take on squall-line-type characteristics such as bow shapes. The principal band however is a unique feature of TC. A conceptual model (Barnes et al. 1983) explaining the dynamics
was recently verified by aircraft observations (HH08). The convection in the principal rainband is fed by $\theta_v$-rich air following the classic “in, up and out” trajectories air parcels experience when following the mean motion of a TC. Mass-continuity requires descending air to replace the convecting air. HH08 showed that two distinct downdrafts on the inward and outward side of the convectively active part of the rainband account for this. They also hypothesize that the generation of vertical vorticity by convection might play a role in changes of the primary cyclone circulation.

The radar image of Hurricane Rita (Figure 1.1) clearly shows the eyewall and the principal band on the eastern side of the storm spiraling inward and connecting to the southern side of the eyewall. Distant rainbands with spotty, buoyancy driven convection are found farther away (e.g. over south Florida). Secondary bands are seen in the inner core near the eyewall.

Figure 1.1. (a) WSR-88D image of Hurricane Rita. (b) MM5 model rain rate of Katrina.

Numerical models are able to reproduce the diversity of rainbands. Figure 1.1 (b) shows a snapshot of rain rate in a simulation of Hurricane Katrina. The inner core is
comprised of the closed eyewall and secondary rainbands circling around it. An intense inner core rainband stretches from the NNW to the WSW at ~ 50 km from the center. A principal band exhibiting individual convective cells is evident mainly on the eastern and southern side of the storm. Convective cells north of the dominant inner core rainband show a somewhat elongated appearance and are subject to the filamentation process as their dynamics become increasingly dominated by the shearing strain associated with the differential rotation of the vortex.

Figure 1.2 shows the different rainband patterns often found in mature TCs. Katrina in the top panel exhibits rainbands of spiral shape whereas Rita (bottom panel) clearly shows a concentric ring of convection at ~60 km radius from the center.
Figure 1.2. Model instantaneous rain rates (in mm hr$^{-1}$) of (a) Katrina at 0848 UTC August 28 and (b) Rita at 2212 UTC September 21 2005.
1.3.2 Inner core dynamics and eyewall replacement cycles

Our understanding of dynamical processes in the inner core of hurricanes has improved dramatically over the last 3 decades. Although not completely unscrambled, meteorologists now understand the processes that lead to the formation of the eyewall and secondary rainbands in the inner core. Early radar observations of hurricanes revealed the existence of spiraling rainbands moving around the center. Several approaches to understand the governing principles of these bands have been made. Although being proposed to be of Rossby type nature quite early (MacDonald 1968), studies in which the bands were hypothesized to be either gravity-inertia waves (e.g. Kurigara 1976, Willoughby 1978) or boundary layer phenomena (Fung 1979; Shapiro 1983) became state-of-the-art theories. It was not until quite recently (Guinn and Schubert 1993) when MacDonald’s ideas of describing the rainbands as “Rossby waves” gained attention again.

Potential vorticity is the basic underlying quantity for the “Rossby waves”, or sometime referred to as “PV waves”, which are usually thought to be large-scale atmospheric waves governing synoptic scale weather features in space and time. These waves need a PV (or vorticity) gradient to exist, provided by the change in PV due to the gradient of planetary vorticity in the meridional direction. A strong PV gradient exists in mature TCs with the maximum value in the center of a storm and decreases radially outward. Theoretical and numerical studies (Guinn and Schubert 1993; MK97; Chen and Yau 2001; Wang 2002b and 2002c) have shown that this PV gradient supports Rossby waves, called “vortex Rossby waves (VRW)”. MK97 has proved theoretically that this type of waves can exist on the radial PV gradient of TCs and derived a dispersion
relationship. They hypothesized that the observed rainbands with extents on the order of 10 km were VRW. Reasor et al. (2000) showed that airborne observations of asymmetries in the inner core of a hurricane are in general agreement with VRW theory. MK97 also found that VRW are able to propagate outward until the ever decreasing PV gradient of the storm and the increasing radial wavenumber does not support wave propagation any longer. This process has implications for wave-mean flow interactions at the “stagnation radius”, a term defining the distance from the center up to where VRW are able to propagate outward. One of hypotheses in MK97 was that the waves can interact with the environmental flow and lead to acceleration of the mean flow due to eddy momentum flux convergence. According to the theory the waves flux momentum inward, so MK97 proposed that the mean flow at the stagnation radius might be accelerated due to the eddy momentum flux convergence. They suggested that observations of secondary wind maxima are a manifestation of this process and thus offered an explanation for secondary eyewall formation. Other studies using assessing the importance of VRW dynamics on the cyclone structure were conducted by Chen and Yau (2001) and Wang (2002a, b). Chen and Yau (2001) used the non-hydrostatic model MM5 to analyze a simulated TC in terms of VRW activity. Wang (2002, a) also carefully analyzed a simulated TC in terms of VRW behavior and found evidence supporting previous theoretical and simplified numerical studies. According to him, wavenumbers 1 and 2 are the most prominent in the inner core region of a TC. Later studies revealed that higher-order wavenumbers are damped due to the strong axisymmetrization in a TC’s inner core due to the shearing strain. The author also conducted a PV and kinetic energy budget analysis and found that the release of latent heat contributed the most to the PV
source terms in both the azimuthal mean and perturbation PV budgets. Wang (2002, b) assessed the impact of VRW on the inner-core structure of a modeled TC. VRW were found to mix momentum from the eyewall into the eye. The author furthermore showed that asymmetric motions due to outer rainbands or VRW are able to perturb the eyewall and could lead to asymmetric eyewall shapes as well as eyewall breakdowns and subsequent reformations. In these cases one can suspect drastic intensity changes over relatively short time scales. These studies however did not address the question of whether or what role VRW play in the formation of secondary eyewalls as suggested by MK97. Kossin et al. (2000), following ground-breaking work of Schubert et al. (1999), deduced the stability of concentric vorticity maxima which are observed when double eyewalls are present. Although not aimed at understanding how these double maxima formed in the first place, they showed with the help of a non-divergent simplified model that nonlinear effects can stabilize the outer vorticity structure and thus contribute to observed longevity of outer eyewalls.

The recent years saw an increase in interest of advancing our knowledge toward understanding how secondary eyewalls form. Early attempts to understand the formation and its interaction with the primary eyewall were done by Willoughby (1979), Willoughby et al. (1982) and Shapiro and Willoughby (1982). In his 1979 paper, Willoughby - who has done tremendous work on this issue - argues that increased friction due to the motion of the cyclone and some sort of resonance between the local inertia period and this friction can generate a new eyewall. Willoughby’s 1982 study postulated the secondary eyewall to be generated by convective-scale downdrafts from the primary eyewall. The air spreads out near the surface and convergence due to the cyclone’s strong
inflow triggers new convection. However, this theory cannot explain why certain TCs do not have secondary eyewall features, nor can it explain the different radii at which concentric rings form (radii of sec. eyewalls can range from 50 to over 250 km, cf. Kuo et al. 2008). The later studies postulated that the secondary circulation generated by the concentric eyewall generates subsidence near the primary eyewall, making the environment more hostile for convection.

A different approach on explaining the formation of secondary eyewall formation requires the interaction between the cyclone and its environment. Eddy momentum flux transfers between the environment and the cyclone can lead to the formation of a secondary eyewall. This theory furthermore requires the presence of an air-sea feedback paradigm. Yano and Emanuel (1991) formulated a nowadays widely accepted wind-induced surface heat and exchange process and coined the term “WISHE”. Nong and Emanuel (2003) used a simplified, axisymmetric model to study the interaction of a mature cyclone and its upper-level environment in terms of secondary eyewall formation with WISHE playing a critical role. Kuo et al. (2004, 2008) make use of a highly simplified, non-divergent and barotropic vorticity model to investigate interactions between two patches of vorticity (“binary vortex interactions”). The intention was to yield certain parameters for which the two vorticity structures (one being the “parent vortex”, one representing a rainband) form a final state in which the outer vorticity blob forms a secondary ring around the stronger inner vortex. Their model was able to account for the wide range of different sizes and intensities TCs were observed to go through eyewall replacements. A key role was assumed by the vorticity gradient outside of the inner core. Although presenting solid results, the simplicity and highly idealized
assumptions in the aforementioned theories such as axisymmetry or non-divergence pose the question whether the results are truly applicable to real TCs and observed intensity changes due to multiple eyewall formations. Kuo et al.’s studies for example are purely based on vorticity arguments and do not address any changes in the wind field. It was not until quite recently that full-physics models were used to study EWRCs. Furthermore, the process of axisymmetrization was found to be important for double eyewall formations. Kuo et al.’s studies show this process in a simple form very nicely. The parent vortex stretches and strains the accompanying vorticity patch until it forms a homogeneous ring around it. The underlying principle is the differential rotation that poses shearing deformation air parcels. Notable studies on axisymmetrization were also conducted by Melander (1987) and MK97. Terwey and Montgomery (2008, hereafter TM08) extend the pure axisymmetrization of a rotating vortex to account for the generation of vertical vorticity by convection. They use a full-physic model with idealized initial conditions to simulate a TC undergoing secondary eyewall formation. The hypothesized theory is probably the most comprehensive theory today and requires a vorticity gradient outside of the inner core, and an increasing filamentation time with radius. This is usually given in TC since the differential rotation decreases outward. Furthermore, TM08 propose that larger CAPE and the WISHE feedback as well as are important for secondary eyewalls to form. A further critical role in their proposal is turbulence theory. The convection at some distance from the center creates a horizontal jet (cf. Barnes et al. 1983, HH08), which enhances turbulence. Axisymmetrization increases the projection of kinetic energy onto the azimuthal mean. Finally, the unstable WISHE feedback loop leads to growth of a concentric ring of convection. The drawback of TM08 is that the model is initialized with
idealized conditions and does not account for interactions with the environment of the storm. All asymmetries arise from intrinsic processes whereas real TC often exhibit asymmetric structures dating back to their genesis stage, or are due to motion or shear.

There have been some studies focusing on complete different reasons for the generation of concentric eyewalls. Most of these approaches however could be rejected as they did not play a role in more recent studies, but may be nevertheless important in single cases. Topographic forcing (Hawkins 1983) or ice microphysics (Willoughby et al. 1984) were not found to be of major importance as concentric eyewalls have been observed far from land. Ice microphysics are also not crucial for EWRCs, they also happen in numerical simulations with only warm rain. As a summary it can be said that axisymmetrization seems to play a major role in the formation of secondary eyewalls. Also, as shown by Kuo et al. (2004, 2008) and TM08, the generation of vertical vorticity or presence of strong vorticity may be of importance.

1.4 Science objectives and working hypothesis

As proposed in previous studies (e.g., MK97), VRWs generated near the primary eyewall propagate outward to a stagnation radius that was determined by the radial wavenumber and the symmetric PV profile of the storm. These waves can interact with the mean vortex in the sense that a conversion of EKE into mean tangential flow occurs. This process may lead to a secondary wind maximum in the azimuthally averaged flow which is a manifestation of a secondary eyewall. TM08 generalized this idea with a full-physics model and speculated that VRW may interact with an ambient $\beta$-skirt and an environment conducive for organized convection. However, they were not able to
identify how the favorable region formed in the first place. Both RAINEX observation and high-resolution model forecasts of Rita have shown a secondary wind and vorticity maximum in the rainband region in Rita. There is a principle rainband similar to that described in Willoughby et al. (1982) in Rita. Our working hypothesis is that PV generation in this persistent rainband region is a key factor contributing to the secondary eyewall formation in Rita. If this is the case, the outer environment in Rita rainband region may be different than that of Katrina. Another question is whether the VRW play a role in the formation of the secondary eyewall as speculated in previous studies. Our main science objective is to shed some lights in these complex interactions between the storm inner core and rainbands and aim to better understand and predict hurricane structure and intensity change.

1.5 Outline

Chapter 1 gives an overview of the current standing in terms of intensity change related to internal and internal-environmental processes in TCs. We pose specific science questions which address processes not well understood when secondary eyewall formations are concerned. Our working hypothesis is presented. Chapter 2 explains the way we want to deal with the aforementioned intentions of this thesis. A synopsis of the two hurricanes exemplifying the processes that might lead to the formation of secondary eyewalls is presented. Furthermore, the model is described and the way the data collected that leads us to compare both model results and observations. Chapter 3 is dealing with the analysis of the model output in order to understand the different PV structure in both space and time in the two storms. A detailed VRW analysis will elucidate how/if VRW
are a key player in the formation of the secondary eyewall in Rita. In Chapter 4, we analyze the PV budget equation with respect to how convectively generated PV alters the PV structure of Katrina and Rita and what implications this has on the formation of the secondary ring. An eddy momentum flux divergence will furthermore shed some light on the wave-mean flow interactions proposed by several previous studies. Chapter 5 concludes this thesis and summarizes our findings. We will compare the model observations with aircraft observations to further validate the results of the model output analysis.
Chapter 2

Methodology

2.1 The numerical model

The numerical model used in this study is the Fifth-Generation Penn State University/National Center for Atmospheric Research non-hydrostatic mesoscale model (MM5) (Grell et al. 1994, Dudhia 1993). To capture the long lifecycle of hurricanes and to resolve the inner-core structure, Chen and Teneralli (2001) developed a vortex-following nested grid that allows the model to be integrated for 5 days or longer at very high resolution (~1-2 km) in the inner most domain. During the RAINEX field program, a triply nested system with 15, 5, and 1.67 km grid spacing, respectively, was used for real-time forecasts and aircraft mission planning. The two inner domains move automatically with the storm. The domain sizes for each of the inner nests are 121x121 and 151x151, respectively. There are 28 sigma-levels in the vertical with about 9 levels within the atmospheric boundary layer. The model has been used to simulate Hurricane Bonnie (1998) (Rogers et al. 2003), Hurricane Georges (1998) (Cangialosi et al. 2006), and Hurricanes Floyd (1999) and Frances (2004) (Chen et al. 2007). These studies have shown that using 1.67 km grid spacing to resolve the inner-core (eye and eyewall) structure is a key in simulating hurricane evolution and intensity change. Figure 2.1 shows an example of the model nested-grid domains used during RAINEX.

We use an explicit moisture microphysics scheme and a slightly modified Kain-Fritsch (K-F) cumulus parameterization (Kain and Fritsch 1993) on the 15 km grid, and the explicit moisture scheme only on the 5 and 1.67 km grids. The microphysics scheme
used is based on Tao and Simpson (1993). The inner core of hurricanes is simulated explicitly in cloud-resolving mode. Modifications to K-F parameterization include detrain of 30% hydrometeters to the resolvable grids and a higher vertical velocity threshold for initiation of convective clouds, which is more suitable for the tropical oceanic conditions. The Blackadar PBL scheme (Zhang and Anthes 1982) is used on all grids, but over water we include a modification based upon Garret (1992) in which we introduce different roughness scales for temperature $z_t$ and moisture $z_q$, which is different that of $z_o$.

The model output used in this study is from the forecasts of Hurricanes Katrina and Rita during RAINEX. The GFDL forecast fields were used as initial and boundary conditions for the 5-day Katrina forecast. The model was initialized at 0000 UTC 27 August 2005. The NOGAPS forecast fields were used for Rita from 0000 UTC 20 September – 0000 UTC 25 September. The MM5 output was re-gridded onto a cylindrical grid for analysis in a storm-relative framework. For the detailed post-processing the model output was saved every 12 minutes to resolve inner core high-frequency fine scale features such as propagating VRW with lifetimes of or less than a few hours. PV fields were computed from the model output.
2.2 Observational datasets

2.2.1 Aircraft observations during the RAINEX field program

Hurricane Katrina and Rita were sampled frequently during the RAINEX field program. The airborne observations in these storms allow for investigation of the evolution in more detail than it otherwise would have been possible. These observations are comprised of flight level data, Doppler radar and dropsondes. Three aircraft with Doppler radar (two NOAA WP-3D and one P-3 operated by NRL of the U.S. Navy)
gathered copious amounts of data. Reflectivity and the 3-dimensional wind field are readily obtained after processing the raw data. From the wind field the vorticity can be calculated. The NRL P-3 was equipped with the ELDORA (Electra Doppler Radar) which is able to provide very high resolution observations on the order of 400 meters, the Doppler radar on the other aircraft have horizontal resolutions of 2 km after the quality control process. These high resolution data is of great use when the structure on a convective scale is important such as in fields which are generated by convective up- and downdrafts. Real-time model simulations allowed the researchers to modify the flight program and thus sample the areas of the storms which proved to be of particular relevance to the science objection. Analysis of simulations run in forecast mode at RSMAS offer another approach to shed light on the complex interactions between a hurricane’s inner core and its outer environment which determines its structure and intensity. While observations of such powerful storms over the open oceans are usually scarce, the Hurricane Rainband and Intensity Change Experiment (RAINEX) taking place that year provided researchers with an unprecedented amount of data gathered by research planes. Intended at providing insight into intensity changes due to interactions between a hurricane’s inner-core and outer rainbands, data obtained by multiple aircraft flying in the same storm are compared to model simulations to better understand these processes.
2.2 Satellite data

The NASA Special Sensor Microwave/Imager (SSM/I) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) are useful tools to follow the evolution of hurricanes. The satellite sensors allow for identifying regions of intense convection under cloud cover. The SSM/I swath width is 1394 km while the width of a TMI swath is 759 km. The narrower swath of the TMI product features larger resolution. The SSM/I swaths are north/south, while the TMI are NE to SW and SE to NE. Between the swaths there is no coverage. From the directly measured brightness temperature an estimate of the local rain rate is derived. When a TC is out of range of reconnaissance flights these satellite products are the only tool that allows us to investigate the structure of storms. Usually it is this satellite imagery that shows the formation of secondary eyewalls before other products do. However, due to the sporadic overpasses and instant images the evolution of EWRCs is not captured. So it is difficult to see why or from what rainband feature a secondary eyewall has formed.
Chapter 3
Symmetric structure of Hurricanes Rita and Katrina (2005)

3.1 Synopsis

3.1.1 Hurricane Katrina

Katrina was an extremely powerful category 5 hurricane with a maximum wind speeds of 150 knots and a minimum sea level pressure of 902 mb at peak intensity in the Gulf of Mexico. Although the storm weakened significantly before making landfall on the northern Gulf coast, it will be remembered as one of the most devastating natural disasters in US history. Katrina’s formation was complex and involved a tropical wave and the mid-level remnants of Tropical Depression Ten (TD 10) which dissipated due to strong vertical westerly wind shear 825 nautical miles (NM) east of Barbados. While the depression’s low-level circulation dissipated, the mid-level remnant vortex could be traced moving north of the Leeward Islands on August 18-19. Convective activity increased with this feature as a tropical wave originating from the west coast of Africa merged with the circulation north of Puerto Rico. Upper level winds in this area became more favorable, i.e. the shear lessened, as the system moved northwestward and consolidated. On August 23, it was classified a tropical depression (TD 12) while over the southeastern Bahamas. The intensity evolution of Katrina starting at 0000 UTC 24 August is shown in Figure 3.1. Arrows in this figure mark the times when the storm was under RAINEX aircraft surveillance. Deep convection increased and the depression became better organized and was upgraded to Tropical Storm (TS) Katrina at 1200 UTC 24 August while moving northwestward. The cyclone continued to become more
symmetric and vertically stacked. The increasing coherence of the vertical structure made it experience a different, deeper layer steering flow. Katrina subsequently made a turn to the west, towards Florida. It intensified further and reached hurricane strength at 2100 UTC August 25, shortly before making landfall near the Broward – Miami-Dade county line. NWS WSR-88D Doppler radar observations suggested that Katrina’s maximum wind speed was near 70 kt when it came ashore. Northerly wind shear due to an upper level anticyclone centered over the northeastern Gulf of Mexico lead to a pronounced wavenumber 1 asymmetry in convection and rainfall with largest amounts on the cyclone’s southern side. Katrina traversed the Florida peninsula in roughly 24 hours.

Figure 3.1. Intensity evolution of Hurricane Katrina from National Hurricane Center (NHC) best track data. Blue is maximum surface wind speed, green minimum sea level pressure. Arrows indicate RAINEX flights into the storm.
Its eyewall stayed remarkable intact while over land and Katrina weakened to a 60 kt TS for a period of one hour early on August 26. This is not reflected in Figure 3.1 because the best track data is incremented into 6 hour periods. Katrina rapidly intensified upon emerging into the Gulf from 65 kt to 95 in the 24 hour period from 0600 YTC August 26-27 (the definition for rapid intensification is an increase in intensity of ≥30 kt in 24 hours). The subsequent stagnation in intensity on the 27th can be explained by an EWRC. The small inner eyewall with a mere diameter of < 6 NM deteriorated and an outer ring of convection became more prominent. Figure 3.2 shows the rain rate estimates observed by the Tropical Rainfall Measuring Mission’s (TRMM) Microwave Imager (TMI). The small eyewall at 2148 UTC August 26 is replaced by an outer eyewall on August 27. Red circles in Figure 3.2 indicate the eyewalls at the respective times. However, due to the lack of direct wind observations the a concise statement about the EWRC cannot be made. The new eyewall contracted into a well defined symmetric ring by 0000 UTC August 28, marking the second period of rapid intensification in Katrina’s life cycle. Katrina intensified from 100 kt (category 3) to 145 kt (category 5) in just 12 hours and reached its peak intensity of 150 kt at 1800 UTC August 28. A well defined eye in visible and IR satellite imagery provided further evidence of a very powerful hurricane. The contraction of the eyewall during the rapid intensification was not accompanied by a contraction of hurricane and tropical storm force wind radii. These radii in fact increased (Knabb et al., 2006) making Katrina not only very intense but also extremely large. Interestingly, observations show that Katrina weakened significantly before it reached the Louisiana coast while the wind field again broadened. The quick weakening from peak intensity to 110 kt in 18 hours is still a matter of discussion. One reason might be the
process depicted by the numerical models, i.e. formation of an outer eyewall-like feature. Furthermore, increasing shear and entrainment of dry air could have adversely affected the convection in the inner-core. Katrina made landfall with estimated 110 kt winds at 1110 UTC 20 August near Buras, Louisiana. Further rapid weakening occurred due to increased surface friction over land and the lack of latent heat fluxes to sustain the deep convection. The hurricane continued to move northward, weakening into a TS at 0000 UTC 30 August. Finally, Katrina degenerated into an extratropical low 24 hours later which was absorbed by a frontal zone over the eastern Great Lakes.
Figure 3.2. Rainrate estimated from TRMM TMI (in inch hr\(^{-1}\)) for Katrina at (a) 2148 UTC 26 August 2005, (b) 2052 UTC 27 August 2005. Red circles indicate the eyewall at the respective times. From Navy NRL Tropical Cyclone Page [http://www.nrlmry.navy.mil/tc_pages/tc_home.html]
3.1.2 *Hurricane Rita*

Hurricane Rita was another intense hurricane with maximum surface winds of 155 kt and a minimum sea level pressure of 897 mb. Although Rita weakened to a category 3 storm prior to landfall in western Louisiana, coastal regions suffered from severe storm surge damage. Rita’s pre-genesis stage can be traced back to a tropical wave leaving western Africa on September 7 and the remnants of a cold front in form of a surface trough. This surface trough detached from the dissipating frontal boundary on 15 September a couple of hundred miles north of the Leeward Islands and began

![Figure 3.3. Same as Fig. 3.1, but for Rita. Arrows indicate RAINEX flights into Rita, the dashed arrow marks a joint RAINEX-NHC mission. The red shading indicates the time Rita underwent the EWRC.](image-url)
drifting westward, being steered by the subtropical high. The tropical wave merged with the surface trough north of Puerto Rico on September 17. Shower activity increased while upper level conditions became more favorable for cyclogenesis as a mid to upper tropospheric low drifted westward over Cuba, diminishing the shear over the system. Gradual organization occurred and a tropical depression is estimated to have formed by 0000 UTC September 18 north of the Dominican Republic. The intensity evolution is given in Figure 3.3 with arrows indicating the times research aircraft were investigating the storm. Rita slowly intensified as it moved west-northwestward. Once the storm was in the Strait of Florida, intensification rates increased significantly and the storm reached hurricane intensity at 1200 UTC September 20 100 NM east-southeast of Key West, Florida. A remarkable period of rapid intensification followed. Favorable atmospheric conditions and the deep, warm waters of the Loop Current laid the foundation for Rita’s ensuing strengthening. The wind speed reached 145 kt by 1800 UTC September 21, only 36 hours after the storm became a hurricane. Rita reached peak intensity at 0300 UTC September 22 with 155 kt. At this time, the hurricane had already begun to turn toward the west-northwest, following the deep layer steering flow around the subtropical high which was centered over the southeastern US. After reaching peak intensity, structural changes occurred and Rita’s eyewall weakened later on September 22 after an outer ring of convection and an associated secondary wind maximum had formed. Max. wind speeds fell to 125 kt by 1800 UTC that day (Figure 3.3). This EWRC will be at focus in this study. Wind shear and cooler SSTs did not favor re-intensification and led to slow weakening after 1200 UTC September 23(Figure 3.3). This weakening continued as the storm turned further to the northwest, and wind speeds decreased to 110 kt by 1800 UTC
September 23. The rate of weakening remained constant and Rita made landfall at 0740 UTC September 24 in extreme southwestern Louisiana with an estimated intensity of 100 kt (category 3). Rita weakened upon landfall, becoming a tropical storm not even 5 hours after landfall. The storm continued to move inland, headed towards the north and finally making a turn to the northeast. The tropical system degenerated into a remnant low on September 26 and lost its convection. Its remnants were absorbed by a frontal zone located over the southern Great Lakes.
3.2 Model forecasts and verification

3.2.1 Track and intensity

A comparison of the simulated storm tracks against the National Hurricane Center’s (NHC) best track data is given in Figure 3.4. The MM5 simulation of Katrina was initialized when the storm was in the southeastern Gulf of Mexico.

The modeled hurricane initially had a northwest bias (Figure 3.4 (a)) as the MM5 did not account for the due westward motion during the first couple of hours. In terms of landfall location the model did an excellent job. However, the landfall timing in the model was about 6 hours too early. Rita was initialized with NOGAPS boundary conditions when it
was south of the Bahamas (Figure 3.4 (b)). Again, the simulated storm took a northwestward track early in the forecast period whereas the real storm moved only slightly north of due west. Furthermore, the simulated Rita moved faster than the real storm which had implications on the intensity of the simulated storm.

In general, the intensity of the numerically simulated cyclones shows good agreement with observations. Figure 3.5 shows an intensity comparison of model wind speed and data from the NHC best track. The model captured Katrina's nearly steady phase on August 27 when the newly formed eyewall was contracting (see Ch. 3.1.1) as well as the rapid intensification on August 28. It did not account for the weakening trend

![Maximum Surface Wind Speed - Katrina](image)

![Maximum Surface Wind Speed - Rita](image)

Figure 3.5. Maximum surface wind speed from MM5 forecasts (blue) and the NHC best track data (black) in (a) Hurricane Katrina from 0000 UTC 27-30 August 2005 and (b) Hurricane Rita from 0000 UTC 21-25 September 2005.
before landfall, which began late on August 28. The model also captured Rita's rapid intensification on September 21 but underwent the eyewall replacement cycle and associated weakening 12 hours too early (Figure 3.5 (b)). For this reason the simulated Rita never reaches the high wind speeds that have been recorded by aircraft reconnaissance flights. Furthermore, the real-world Rita did not intensify after its EWRC as predicted by the simulation (blue line, after 1200 UTC September 22) due to increasing shear (Knabb et al., 2006). It should be mentioned here that the best track represents only the best estimate of the real intensity. Small sampling area, different wind speed measuring techniques, averaging issues and other factors suggest that the real intensity can be different from the best track data. Figures 3.4 and 3.5 show 1-hour linear interpolations (black lines and squares) of the 6-hourly incremented best track data resulting in the smooth appearance of the observed intensity values compared to the noisier 1-hourly model output.

The azimuthally averaged wind speed evolution from the MM5 (Figure 3.6) clearly shows the different evolutions of both storms: Katrina shows a uniform intensity evolution and never forms a secondary wind maximum (monotonic wind speed gradient outside of the radius of maximum winds (RMW) at ~ 25 km). In contrast, Rita undergoes the aforementioned EWRC (September 22, Figure 3.6 (b)). This contrary behavior allows us to look for differences in the inner core - rainband interactions which are possibly triggering the formation of a secondary wind maximum and thus lead to the observed and simulated intensity fluctuation related to the EWRC (Figure 3.5).
Figure 3.6. Time-radius (Hovmöller) diagram of wind speed (in m s$^{-1}$) at 700 mb in (a) Katrina from 1200 UTC 27 – 1200 UTC 29 August, (b) in Rita from 0000 UTC 21 September – 0000 UTC 23 September.
3.2.2 Storm structure from observations and model

For the following analysis, we calculated the vertical vorticity component from the 3-dimensional wind field retrieved by the airborane dual Doppler radar. Two flight legs across the storm center spanning roughly one half hour each have been composited in order to get a vorticity distribution covering as much of the storm as possible. The retrieved vorticity field is then compared against the model vorticity at the same level (700 mb). It should be noted that the exact times of observed vorticity and model output do not match because the simulated Rita underwent the EWRC 6 hours before the real storm and thus its evolution is faster. Figure 3.7 (a) shows Doppler radar derived vorticity and (b) model vorticity at the 700 mb level. The exact time is given in the figure caption. The lack of retrievals in the eye is due to the lack of scattering objects (hydrometeors). In general, the common vorticity structure of TCs can be seen with maximum values inside the RMW which as at ~ 25 km radius. However, the observations and the model show that the vorticity does not decrease uniformly outward but shows elevated values related to rainbands especially outside 50 km. The vorticity in the rainbands is generated by tilting and stretching of horizontal vorticity (HH08). The model vorticity shows more distinct smaller scale features which are not apparent in the observed field for two reasons: 1) the horizontal resolution of the Doppler radar is 2 km, while the model resolution in the inner most domain is 1.67 km. 2) The radar image is composited (temporally averaged), whereas the model output is a “snapshot”. This means that the observed vorticity field shows a smoothed version of the actual vorticity field so that rapidly evolving small scale features are not discernible.
Figure 3.7. Comparison of vertical vorticity at the 700 mb level from (a) aircraft Doppler radar observations and (b) MM5. For the observed vorticity, two flight legs through the storm center have been composited (between 1506 and 1617 UTC 21 September 2005), (b) is a snapshot from 1800 UTC 21 September 2005.
Figure 3.8 shows the vorticity distribution approximately one day later. In the observed field, the formation of a ring structure of elevated vorticity is evident at 50 – 60 km. The model vorticity still shows more distinct banding features, but it can be seen that there is a developing vorticity maximum at 50 km. One hour later, the ring became more coherent and better defined (Figure 3.9). On the next flight, the secondary ring of vorticity became stronger (max. vorticity = 4 x 10^-3 s^-1, Figure 3.10) and contracted by ~ 10 km. The simulated vorticity field behaved accordingly (Figure 3.10 (b)). Finally, the storm continued the EWRC when there was no research flight mission into Rita. The next sampling occurred on the following day (September 23, Figure 3.11) and shows a vorticity pattern similar to the one in Figure 3.7. The storm had completed the cycle and replaced the original eyewall with the secondary eyewall which became the dominant primary eyewall.

This chapter showed that the MM5 reproduced the structural evolution of Rita as observed by aircraft Doppler radar observation. Although the exact times are not the same, we can argue that analyzing the MM5 forecast fields will give us the opportunity to see which processes lead to the secondary eyewall formation in the real-world Rita.
Figure 3.8. Same as Fig. 3.7, except for (a) 1435 – 1638 UTC 22 September 2005 and (b) 1048 UTC 22 September 2005.
Figure 3.9. Same as Fig. 3.7, but for (a) 1702 – 1818 UTC 22 September 2005 and (b) 1112 UTC 22 September 2005.
Figure 3.10. Same as Fig. 3.7, but for (a) 1856 – 2100 UTC 22 September 2005 and (b) 1300 UTC 22 September 2005.
Figure 3.11. Same as Fig. 3.7, but for (a) 1640 – 1802 UTC 23 September 2005 and (b) 1000 UTC 23 September 2005.
3.3 Evolution of the symmetric structure

3.3.1 Potential vorticity (PV) distribution

PV is a fundamental quantity in atmospheric sciences. It represents a combination of both dynamic (vorticity) and thermodynamic (static stability) aspects of atmospheric flows and is usually expressed as

\[ P = \rho^{-1} \zeta \cdot \nabla \theta \]  

(3.1)

in geometric coordinates. Hoskins et al. (1985) comprehensively studied the use of PV in terms of predicting and analyzing large scale weather patterns in the mid-latitudes. They applied the “invertibility principle”, meaning that the distribution of PV in a confined area is sufficient to deduce all other dynamical and thermodynamical variables such as the velocity vector, (potential) temperature and geopotential height if boundary conditions and balance criteria are specified. PV has also been used extensively to study dynamics of tropical cyclones (e.g. Shapiro and Franklin 1995). Although PV is readily computed from numerical simulations, it is difficult to obtain PV distributions from observations in TCs. Observational studies lack the knowledge of the PV distribution due to the difficulty to obtain static stabilities and rely on using the vorticity field in order to examine governing dynamic processes (e.g. HH08). In this study however, the PV field and especially the areas of PV generation are of particular interest. Of advantage is that the PV field closely resembles the vorticity field and only in the eye noticeable deviations from each other are found because of the unique thermodaynamic properties of the hurricane eye. Figure 3.12 shows the 1-hourly and azimuthally averaged PV (solid) and vorticity (dashed) distribution in the simulated Katrina for two different times (red/blue).
Figure 3.12. (a) Azimuthally and 1-hourly averaged PV (solid) and vertical vorticity (dashed) at 700 mb from the model for Katrina at 0300-0400 UTC and 1900-2000 UTC August 28. (b) Same as (a) but enlarged ordinate.
during the intensification period. The vorticity in the inner core increases between 0300
and 1900 UTC, however the PV increases by a larger amount (Figure 3.12 (a)). Note that
the PV and vorticity distribution have a similar shape at the first time (ring structure with
a maximum at 15 km) whereas 16 hours later the PV distribution assumed a monopole
geometry with the maximum in the center while the vorticity profile is still exhibiting a
ring structure (red dashed line). In Figure 3.12 (b) the ordinate has been enlarged to
further highlight the similarities between PV and vertical vorticity. Both the dashed and
solid line follow each other closely.

Several studies aimed to understand structure and intensity changes of TCs make
use of the PV field, and some explanations for 3-dimensional dynamic processes in the
inner core can only be explained if the PV distribution in this region is regarded (e.g.
MK97). For other purposes, the environmental PV field is examined in order to better
understand steering flows which determine the path of a TC. For these purposes PV can
be inverted to yield both dynamic and thermodynamic fields of the TC itself and its
interaction with synoptic-scale environment (Wu and Wang 2000). However, it should be
noted that TCs are different from synoptic-scale weather systems for which the
conservation and invertibility principle of PV is generally applicable as described by
Hoskins et al. (1985). First, PV is far from being a conserved quantity in a TC, especially
if smaller scales at or below the cyclone scale are considered. Vigorous convection in the
eyewall and rainbands generates copious amounts of PV through latent heat release. This
heat tends to stabilize the atmosphere below the level of maximum heating in the lower to
middle troposphere and thus leads to an increase in PV. Although the static stability will
be weakened above this level, generation rates usually exceed the amount of PV depleted
above the level of maximum heating (Schubert et al. 1999). The high wind speeds found in TCs give rise to strong surface friction which is a major sink of PV. Furthermore, PV is depleted in regions where evaporative cooling reduces the static stability.

Second, the flow in a hurricane can only loosely be described as steady, and tremendous rates of intensification and weakening have been observed. Hurricane Wilma (2005), certainly an extreme case and not representative of the average TC, intensified by 90 kt during a 24 h period and featured deepening rates of 9 mb per hour (Pasch et al., 2006). In such cases the assumption of gradient flow (the magnitude of the velocity vector is constant) cannot be sustained anymore and the flow has to be described as unbalanced. Similar accelerations of the wind are found in numerically simulated TCs (e.g. TW08 or Chen, 2002).

Shapiro and Franklin (1995) conducted an analysis to describe Hurricane Gloria from a PV perspective. Due to the lack of thermodynamic observations they had to rely on balance conditions to be able to describe the dynamics by using PV. They compared the observed winds with the wind speed obtained from the balance condition. In turned out that in the inner regions of the storm the actual wind was supergradient. The disadvantage of unbalanced flows poses some constrains on the original aim of PV, i.e. the invertibility principle, and make it difficult to apply it on TCs. However, Wang and Zhang (2003) successfully applied the PV conversion principle to a simulated hurricane. They concluded that it was possible because the modeled cyclone was highly axisymmetric and in a quasi-balanced state, however they also stated that it is unclear whether the principle holds for highly asymmetric or rapidly evolving storms. Even
though the mentioned constrains limit the powerful use of PV, it is an important tool for our understanding of underlying dynamic principles governing the evolution of a TC.

It has been mentioned before that for an intensifying TC the azimuthally averaged PV structure features a ring of elevated PV near the eyewall. However, Schubert et al. (1999) showed that a monopole PV structure with maximum PV values in the center marks the end of the intensification period. Instabilities in the eyewall grow and eventually break, mixing PV from the eyewall region into the eye, and thus increase the amount of PV there. Figure 3.13 clearly shows this evolution. The colored shading in Figure 3.13 is the base-10 logarithm of azimuthally averaged PV, the white contours indicate the azimuthally averaged wind speed in Katrina (a) and Rita (b). The Hovmöller diagram shows the formation of a monopole after the intensification period has ended. Figure 3.13 (b) displays the formation of a secondary maximum of PV between 70 and 100 km early on September 21 in Rita. This secondary maximum contracts with time and becomes better defined. On September 22, a well defined secondary PV maximum slightly inside of a secondary wind maximum indicates that a secondary eyewall has formed. This eyewall increases in intensity (white contours) and becomes stronger than the primary eyewall after 1200 UTC September 22. Figure 3.14 shows a close-up of the inner core of Katrina (a) and Rita (b). Again, the colors are azimuthally averaged PV (in m\(^2\) s\(^{-1}\) K kg\(^{-1}\)) and contours denote the wind speed. It is difficult to see the secondary PV maximum on a linear scale (as opposed to the log-scale in Fig. 3.10) before 1200 UTC September 22. This highlights the large amounts of PV found inside the eyewall and shows that PV values outside the immediate inner core are much smaller but nevertheless important when it comes to structural processes such as EWRC (Figure 3.13). Figure 3.13
Figure 3.13. Azim. averaged PV (colors, displayed in log-scale) and wind speed (contours, in m s$^{-1}$) at 700 mb. Data from MM5; (a) Katrina, (b) Rita.
Figure 3.14. Time-radius diagram of azim.-aver. PV (colors, in m$^2$ s$^{-1}$ K kg$^{-1}$) and wind speed (contours, in m s$^{-1}$) at 700 mb in (a) Katrina and (b) Rita.

also shows that the secondary maximum of PV precedes the formation of a secondary wind maximum.
3.3.2 Evolution of rain, wind and PV

The azimuthally averaged PV distribution is a measure for intensity and structure of a TC. It is obvious that large PV values are found in areas where the vorticity is large, thus near the center (eyewall region) of intense storms (see Ch. 3.3.1). For intensifying storms, the radial PV gradient is usually positive from the center of the eye outward to a point where it reverses sign. Beyond this region (which is still inside the RMW), the PV gradient is very steep and becomes flatter as the radius increases. Figure 3.15 shows the azimuthally and 1-hourly averaged PV, rainrate and wind speed in Katrina at 4 different times between 0300 and 2000 UTC August 28. To highlight the PV distribution outside the radius of maximum PV, the ordinate has been adjusted and maximum PV values are beyond the scale and thus not shown. Katrina had a very steep PV gradient up to 25 km outward (red line). The strong PV is related to excessive vertical vorticity due to the rotating winds (curvature vorticity) as well as cyclonic shear produced by the velocity gradient (slow winds in the eye, high wind velocities in the eyewall region). Adjacent to this region is more subtle PV gradient outward from 25 km. Between 25 and ~100 km the PV gradient is negative, albeit not monotonic (in an azimuthal averaged sense) due to perturbations such as rainbands. This area is commonly known as the “vorticity” or “PV skirt”. Beyond 100-125 km, the PV gradient becomes flat. From the theory, we know that outward propagating VRW are only possible where a PV gradient exists (i.e. inside ~100 km, see Chapter 1.3.2). The temporal evolution of Katrina’s azimuthally averaged PV gradient shows that a plateau of elevated PV is generated between 25 and 60 km (Figure 3.15, 1900 UTC). Comparison with the averaged rain rate reveals that this PV is probably generated by convectively active rainbands in this region (blue line in Figure 3.15, at
0900, 1400 and 1900 UTC). After 0300 UTC the PV gradient between 25 and 50 km becomes less monotonic; the strong decline near the eye does not change, but the plateau between 25 and 50 km develops. A secondary, steepening PV gradient is found between 50 and 70 km (after 1400 UTC) which is part of the PV skirt in this region. The changing PV profile has implications on the wind field. PV generation in the rainband requires the wind field to adjust accordingly. Therefore, the wind speed outside of the PV maximum has to increase in order to “produce” the high vorticity due to increased cyclonic shear (analogous to the cyclonic shear induced vorticity inside the RMW). This process is well documented in several studies (e.g. HH08). A “mid-level jet” is usually observed radially outside of the local PV maximum. Due to the spiral nature of rainbands this jet is not very

Figure 3.15. Azimuthally averaged PV (red), rain rate (blue) and wind speed (black) from MM5 in Katrina. Each panel represents an average over 1 hour, centered on the time given in the title of each panel.
well pronounced in azimuthal averages such as Fig. 3.15 but nevertheless discernible as a
minor wiggle in the wind field (Figure 3.15, black dashed line).

Figure 3.16 displays the same variables except for Rita. The analyzed period is
over a longer time to capture the EWRC in Rita (0800 UTC September 21 – 1800 UTC
September 22). The first major difference is seen in the azimuthally averaged rain rate. A
distinct moat region between 25 and 50 km with a minimum in the rain rate was not
evident in Katrina. Rain rates are below 5 mm hr$^{-1}$ at this radius between 0800 and 2000
UTC September 21. This moat has also been observed during the RAINEX field program
(Houze et al., 2007). The secondary maximum in the rain rate between 75 and 125 km is
related to the active principal rainband projecting well onto the azimuthal mean in Rita.
Figure 3.16 shows that the local maximum in the rain rate propagates inward. In terms of
PV, the first panel in Figure 3.16 shows an initial PV profile that resembles Katrina’s.
The inner, steep gradient still exists as it is related to the swirling nature of a hurricane’s
inner core. However, the rain rate maximum at 75-125 km is a distinct feature in Rita.
The next panel (1400 UTC, top right) shows that the PV profile from 25-75 km is not as
monotonically decreasing when compared to the same area in Katrina. The wind field
(black line) shows the same behavior when compared against Katrina. At 2000 UTC
September 21, the PV profile shows the characteristic secondary maximum between 50
and 70 km. The manifestation of this pattern in the wind field is a slowly increasing
secondary maximum (between 70 and 100 km). The PV profile at 1400 UTC has
implications for VRW. The non-monotonic gradient does not allow for radial propagation
of the waves.
The subsequent evolution of the rain rate depicts the EWRC. At 0800 UTC September 22 the peak has narrowed down as the rainband feature evolves into a secondary eyewall and becomes more axisymmetric. At 1400 UTC September 22, the primary eyewall at ~ 17 km has weakened significantly and the secondary eyewall has become the dominant feature. Finally at 1700 UTC, there is little evidence of the primary eyewall left. The wind field follows this evolution and shows a distinct secondary maximum. By 1400 UTC September 22, the secondary wind maximum is stronger than the one original wind maximum adjacent to the primary eyewall. The PV distribution however behaves a little differently. Although there is a distinct secondary peak in the azimuthally averaged PV field, it never becomes stronger than the primary maximum. The shearing vorticity related to the decreasing wind speed inside the RMW and the static stability in the eye lead to far higher PV values within the immediate inner core. Once the secondary PV maximum becomes better defined, the radial gradient is reestablished. This means that the inner core in Rita becomes supportive for outward propagating VRW beyond 25 km. VRW and their effect on the formation of the secondary ring of convection in Rita activity will be analyzed in the following subchapter.
Figure 3.16. Same as Fig. 3.15, but for Rita.
3.4 Vortex Rossby waves

3.4.1 Distinct vortex Rossby waves in Katrina and Rita

Analyses of numerical model simulations have shown that inner core asymmetries in precipitation, PV and vertical velocity are manifestations of vortex Rossby waves (Chen and Yau 2001; Chen et al. 2003). In order to examine our model simulations of Katrina and Rita in terms of VRW, atmospheric fields were Fourier-decomposed into wavenumber 1-4. The inner core asymmetries are dominated by relatively low azimuthal wavenumber. Upon comparing the energy in the respective wavenumbers, it became evident that wavenumbers 1 and 2 are much more energetic than higher wavenumbers. Chen (2008) pointed out that higher wavenumber asymmetries are axisymmetrized quickly by the differential rotation of the vortex in the inner core region. Wavenumbers 3 and 4 are discernible, but the peak in amplitude is not as concentrated as for lower wavenumbers. The Hovmöller diagrams (Figures 3.17-3.22) show a radius-time domain and make it easy to identify radially propagating features. Cross-sections were taken to the east of the storm center. The left-hand panel of Figure 3.17 shows Katrina’s wavenumber 2 components of PV (colored shading) and vertical velocity in black contours with negative values dashed. Most prominent are VRW circling around the steep PV gradients inside and outside the ringlike PV profile with a maximum at ~20 km radius (cf. Figure 3.12 (a), PV profile). Furthermore, at radii greater ~ 30 km, outward propagating VRW are found as evidenced by alternating streaks in red and blue which correspond with positive and negative PV asymmetries (Figure 3.17 (a), between 0900 and 1500 UTC). The amplitude of these waves is much smaller than their not outward propagating counterparts (at 20 km radius) which are manifestations of asymmetries in
the eyewall. The vertical velocity field leads the PV anomaly, by roughly \( \frac{1}{4} \) radial wavelength, which is supporting the argument that these wave features are truly VRW waves and not gravity waves (Chen 2002). The “stagnation radius” proposed by MK97 is seen in so far as wave signals are not found beyond radii greater than 75 - 80 km. Comparison with the PV gradients in Figure 3.15 show that the PV gradient beyond 80 km is too flat to support VRW. The right-hand panel of Figure 3.17 further highlights the wave features, here the colors represent the azimuthally Fourier-decomposed rain rate and the contours denote the respective PV wavenumber asymmetry. Positive rain rate and
positive PV anomalies are highly correlated, stating that the secondary rainbands in Katrina are convectively-coupled VRW. The coupling mechanism creates a positive feedback, the original PV asymmetry induces convection and by moist convective processes more PV is being generated. It should be noted that the amplitude of outward propagating VRW is largest between 50-60 km. Between the eyewall and this region the waves seem to be suppressed (especially between 1200 and 1400 UTC). Figure 3.15 explains this behavior: the radial PV gradient does not allow for VRW propagation due to a flat PV gradient between 25 and 50 km.

Wavenumber 3 components for Katrina are displayed in Figure 3.18. The PV and vertical velocity asymmetries do not exhibit an as coherent structure as the wavenumber 2 components. Outward propagating waves are not readily discernible in these fields, however the rain rate asymmetries with overlaid PV contours make clear that there are waves. These are active in the same region as the wavenumber 2 features. The wavenumber 4 components are similar to the wavenumber 3 components, but again with decreased amplitude (not shown). It is readily inferred from the pictures that VRW of each respective wavenumber are active in the same region, where the radial PV gradient is supportive of their existence (compare with Figure 3.15). The amplitudes of the outward propagating waves peak where the radial PV gradient is steepest (in Katrina: between 40 and 70 km).

The following part aims at comparing both hurricanes in terms of their VRW activity. In Figures 3.19 – 3.22 the left-hand panels show Rita, the right hand panels show Katrina. Due to Rita’s EWRC, which is of particular interest, the analyzed period for Rita is longer. The model output for Katrina is analyzed from 0300-2000 UTC August 28and
for Rita from 0800-1800 UTC September 21/22. Due to this reason the panels displaying variables in Katrina are half blank. The variables shown in Figures 3.19-3.22 are rain rate component (colored shading) and PV component (contours). Figures 3.17-3.18 have shown that PV and rain rate are highly correlated and that the rain rate is making it easier to identify propagating VRW. Figure 3.19 shows that wavenumber 1 is dominant in terms of amplitude in both storms, consistent with the fact that the inner core of intense cyclones is comprised of low wavenumber asymmetries superimposed on a highly symmetric cortex (the symmetric part is equal to the azimuthal mean or wavenumber 0). Usually the wavenumber 1 component is the asymmetry caused by environmental

Figure 3.18. Same as Fig. 3.17, except for wavenumber 3 components.
vertical wind shear or related to the motion of the cyclone (Chen et al. 2006). Convection is increased on the downshear side of the storm and precipitation maxima are found

Figure 3.19. (a) Wavenumber 1 components of rain rate (colors, in mm hr$^{-1}$) and PV (contours) in Rita, (b) same as (a) but for Katrina.

on the downshear-left side. Figure 3.19 shows that Rita’s wavenumber 1 asymmetry increased in the late morning of September 22, with rain rate maxima near 50 km radius. At this time, the EWRC was almost completed and the maxima are collocated with the contracting secondary eyewall. Shear is likely to be the major cause for this increased wavenumber 1 activity in the model. Observations also showed that Rita was affected by increasing shear after the EWRC so that it was not able to reach intensities it had before
the replacement cycle. Wavenumber 2 activity in Katrina is rather continuous with minor fluctuations in the analyzed period whereas in Rita in the first 12 hours a coherent pattern of wavenumber 2 asymmetries is not evident (Figure 3.20). From 2100 UTC September 21 on outward propagating waves do appear beyond 50 km. These features are related to the negative gradient on the outside of the developing secondary eyewall (Figure 3.16, after 2000 UTC September 21). The PV gradient between the primary eyewall and the concentric ring is not conducive for VRW propagation (see Ch. 3.2.2).

Wavenumbers 3 and 4 exhibit similar structures (Figures 3.21 and 3.22). The waves in Rita become more pronounced after 2100 UTC 22 September. These asymmetries are also related to the rainband that consolidates with time and becomes the

Figure 3.20. Same as Fig. 3.19, except for wavenumber 2 components.
secondary eyewall. Wavenumber 3 and 4 VRW propagate farther out than wavenumber 2 features.

The aforementioned moat is another striking difference between the two storms. The lack of VRW activity in Rita between 25 and 50 km is related to the unfavorable PV gradient (see Fig. 3.16) as well as very unfavorable conditions for convection with net-downward motion and drying (Houze 2007). Once the simulated Rita completes the EWRC, outward propagating VRW are evident (Figures 3.19-3.21, after ~ 1200 UTC September 22). This is also supported by the pronounced PV skirt in Figure 3.16 (after 1100 UTC, between 40 and 75 km).

Figure 3.21. Same as Fig. 3.19, except for wavenumber 3 components.
Figure 3.22. Same as Fig. 3.19, except for wavenumber 4 components.
3.4.2 Effect of vortex Rossby waves on storm evolution

In this section we will analyze the effects of outward propagating VRW on the temporal evolution of outer spiral rainbands that take on the form of a concentric ring. In order to distinguish between the spiral nature of a common rainband and the secondary ring structure, a measure has been created that accounts for the density distribution of convective precipitation at a given radius. Grid points with rain rates greater than 12.5 mm hr$^{-1}$ qualify for convective precipitation (Ortt 2007). A large fractional coverage of convective precipitation at a given radius can be due to two reasons: 1) Rainbands are convectively active or 2) a rainband features a circular rather than spiral geometry. A rainband could be perfectly circular but if precipitation is weak and many grid points do not exceed the threshold for convective precipitation, the fractional coverage of convection would be small. On the other hand, many spiraling bands with heavy precipitation may lead to a large fractional coverage of convection at a given radius.

Figure 3.23 shows in colors the fractional coverage of rain rate greater than 12.5 mm hr$^{-1}$ in Katrina. The black contours denote the wavenumber 1 (a) and wavenumber 2 (b) components of PV (cross-sections taken to the east of the storm center). The contours thus indicate areas of VRW activity. Figure 3.23 shows that the convectively active region between 30 and 60 km and between 0900 and 1500 UTC August 28 is clearly related to VRW activity. Figure 3.23 (b) also shows that VRW are able to propagate outward to ~ 70 km radius. However, there is little convection of these features beyond 60 km projecting onto the azimuthal mean.

Another interesting point is the lack of persistence of the areas with a large fractional coverage of convection.
Figure 3.23. (a) Fractional coverage of rain rate > 12.5 mm hr$^{-1}$ (colors) and wavenumber 1 component of PV (contours, cross sections to the east of storm center) in Katrina. (b) same as (a) except for wavenumber 2 component.
Even though VRW are discernible over the whole time period (0300-2000 UTC), maxima in the fractional coverage are well pronounced only between 0900 and 1500 UTC. Figure 3.24 shows the same except for wavenumber 3 and 4 components of PV. Amplitudes of the wave features are much smaller, but the waves can again be related to regions with a large fractional coverage of convecton.

Figure 3.25 displays the same variables for Rita (analyzed period is 0900-1800 UTC September 21/22). Strikingly, the primary eyewall loses its structure while an outer rainband (the principal band) propagates inward (colors). In contrast to Katrina, evidence of the outer rainband is seen at greater radii (125 km at 0900 UTC September 21). This rainband is diffuse in the beginning but consolidates as it contracts with time. Nevertheless, in Katrina (Figures 3.23 and 3.24), no such feature is evident at all. The less coherent structure depicted by this analysis is due to the relatively small amount of grid points covered by convection at large radii. The principal rainband transitions from a typical outer rainband to an eyewall type feature which again has a greater coverage of convection due to its circularity. Furthermore, there is a clear lack of VRW activity in Rita between 0900 and 1800 UTC September 21. This is also evident in Figure 3.26 which displays the wavenumber 3 and 4 components of PV. It is not until after the secondary ring has consolidated enough and generated a PV gradient (see Figure 3.16) that VRW are able to propagate outward. However, these waves do not originate from the primary eyewall but from the secondary ring of convection. It is thus hypothesized that the outer rainband contracts and evolves into a concentric ring without interference of VRW originating from the inner core of the hurricane. Figure 3.25 is consistent with Figures 3.19 – 3.22, which do not show VRW activity between 1200 and 2100 UTC 21

Figure 3.24. Same as Fig. 3.23 except for (a) wavenumber 3 component and (b) wavenumber 4 component.
September. Figure 3.25 furthermore gives evidence of the moat region between 25 and 50 km (0900 – 2100 UTC 21 September) with a pronounced minimum in the fractional coverage of convection between 25 and 50 km. The convectively-coupled VRW are not able to cross the moat because of the unfavorable PV profile (Ch. 3.3.1) and the unfavorable environment. As described before, the developing PV gradient outside of Rita’s secondary eyewall shows distinct VRW activity (after 2100 UTC September 21, outside of 50 km radius). These waves propagate outward to 100 km but seem to lose their convective signal in the fractional coverage due to the increasing amount of gridpoints at larger radii. Once the secondary eyewall and the remnants of the primary eyewall come closer together (after 0900 UTC September 22), connecting bands from the primary PV gradient interact with the secondary eyewall. Figure 3.16 showed that the PV profile at this time is supportive of continuous wave propagation outward from 20 km.

Figure 3.26 shows the same, except for wavenumbers 3 and 4. When the higher wavenumbers are analyzed, a similar result is obtained. The difference from wavenumber 2 asymmetries is the less pronounced onset of wave activity and amplitudes. In general, propagating waves are most prominent in wavenumber 2 asymmetries. Wavenumber 4 activity seems to be more concentrated once the secondary ring consolidates and the fraction of convection exceeds 50 % exceeds 0.5. This happens at 2100 UTC at 60 – 70 km radius.
Figure 3.25. (a) Fractional coverage of rain rate > 12.5 mm hr\(^{-1}\) (colors) and wavenumber 1 component of PV (contours, cross sections to the east of storm center) in Rita. (b) same as (a) except for wavenumber 2 component.
Figure 3.26. Same as Fig. 3.25 except for (a) wavenumber 3 and (b) wavenumber 4 components.
MK97 showed that outward propagating VRW cease to travel at a particular radius where the fading PV gradient of the TC vortex becomes too weak to support the waves. This “stagnation radius” was speculated to be a region of wave-mean flow interactions resulting in an increase of tangential wind speed. The acceleration of the tangential mean flow is determined by the eddy momentum flux divergence (EMFD) and can be expressed with the following equation:

$$\frac{\partial \bar{v}}{\partial t} = -\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \bar{u}'v')$$  \hspace{1cm} (3.2)

where $r$ is radius, $v$ tangential wind and $u$ radial wind. Bars denote azimuthal means and primes deviations therefrom. When Katrina’s EMFD is examined, the main feature is the deceleration of the mean flow in the eyewall region near the RMW (Figure 3.27). The blue line is the mean tangential wind tendency due to eddy momentum flux divergences averaged between 0300 and 0900 UTC August 28. The green line denotes the averaged tangential wind speed and allows for identifying the eyewall. VRW tend to peak in their amplitude at ~20 km, where the PV gradient is steepest, thus their impact on the mean flow is maximum at this radius. Deceleration rates are greater than 11 m s$^{-1}$ hr$^{-1}$ and thus are of substantial amplitude to have an effect on the mean circulation. The waves carry momentum into the eye (Figure 3.27) where the tangential mean wind is accelerated by 3 m s$^{-1}$ hr$^{-1}$. Interestingly, no coherent effects on the mean flow is found outside 40 km. The EMFD fluctuates about the zero line. The stagnation radius seen in the time-radius plots is not evident in this analysis. In Rita (Figure 3.28), the incoherent EMFD signal beyond the innermost core region is also found. In Rita, we averaged the EMFD between 0000 and 0600 UTC September 22 when the secondary eyewall was forming. Momentum flux divergences are alternating in sign in a relatively unperiodic manner. The net impact is
probably slightly positive but yet again not concentrated at a particular radius as stated by MK97. The lack of a strong positive EMFD signal at larger radii is a hint that this process does not play a major role in structure and intensity changes. Thus we conclude that wave-mean flow interactions are negligible for regions away from the immediate eyewall region from a momentum perspective as suggested by the model output.

Figure 3.27. Eddy momentum flux divergence (blue) and azimuthally-averaged tangential wind speed (green, not to scale) at 700 mb in Katrina. Averaged over the time period 0300-0900 UTC 28 August.
Figure 3.28. Same as Fig. 3.27, but for Rita. Averaged from 0000-0600 UTC 22 September.
Chapter 4

Secondary Eyewall Formation in Rita

4.1 PV generation and redistribution

Formation of a secondary eyewall in tropical cyclones can be viewed as the development of an enhanced secondary ring of PV. This chapter addresses the question of how the secondary PV ring developed in Hurricane Rita by examining the PV generation and redistribution using the PV budget equation. Strictly speaking, the PV conservation principle can only be applied in a hydrostatic, dry atmosphere. Schubert et al. (2001) derived the PV equations for a non-hydrostatic, moist atmosphere by replacing the potential temperature with virtual potential temperature in Eq. (3.1). However, moist PV is not a conserved quantity. For the purpose of this study, the budget of “regular” PV is adequate to address the question of PV generation as was conducted in Wang (2002a).

Convectively-generated PV in tropical cyclones has been examined in a number of previous studies. May and Holland (1999) have shown from observations that PV is generated primarily in the stratiform region of rainbands, where the latent heat release in the mid-upper troposphere increases the temperature and evaporative cooling decreases the temperature in lower levels. PV increases as the vertical gradient of potential temperature increases. However, the most rapid PV generation occurs in the deep convective cores where horizontal vorticity is converted into vertical vorticity by tilting and latent heat release is maximum in the mid-troposphere. May and Holland (1999) could not show this due to inadequate resolution of their data where convective cores were not resolved. Examination of Figures 3.7-3.11 and Figure 4.1 clearly shows that
high PV values are correlated with convectively active regions of the TC. The high PV and vorticity regions coincide with large vertical velocity and precipitation values in the rainbands, which occur on a small scale of a few kilometers.

The maximum latent heat release in deep convection occurs in lower to mid-troposphere (Houze 1997). The positive latent heat release and cyclonic vorticity in the inner core region of a tropical cyclone lead to generation of large amounts of PV and ultimately to formation of a PV ring in the eyewall. Similar mechanism for PV generation should be found in the rainband region. HH08 carefully analyzed the kinematic structure of convective elements in the rainbands in Katrina and Rita and concluded that PV generation is generally maximum at the 3-5 km level. Convectively-induced PV in these regions could be a candidate responsible for formation of a secondary PV maximum at the location of a persistent rainbands (in an azimuthally averaged sense) if the convectively-generated PV is larger than the local PV sink such as friction and advection.

4.1.1 PV budget equation

In this study, the PV budget is computed similarly as in Wang (2002, a), except the z-coordinate is used as the vertical coordinate. Studies have shown (HH08) that PV is most effectively generated in regions of the rainband where young convection prevails. Thus the best way to account for this PV generation regime is to decompose the PV budget equation into azimuthal mean and perturbation parts by making use of the Reynolds decomposition.

Eq. (4.1) is the PV budget equation used in this study. In general, Ā denotes the azimuthal average of any variable A.
\[ \frac{\partial \Phi}{\partial t} = -\nabla \cdot \left( \tilde{\Omega} \Phi - \frac{\bar{Q}}{\rho} \tilde{\omega} + \bar{\nabla} \cdot \Phi' \right) \] (4.1)

The left hand side of the equation is the local rate of change of azimuthally averaged PV. The right hand side of the equation is comprised of the sink and source terms. The frictional dissipation term is considered negligible (Wang 2002, a). Note that the equation is in flux form, so the rate of change is expressed in flux divergences. The first right-hand side term is the flux divergence of azimuthally averaged PV by the azimuthally averaged wind vector. This can be explained physically as the PV flux due to the mean vortex circulation. The second term denotes the PV change by the divergence of the product of azimuthally averaged diabatic heating ($\bar{Q}$) and averaged vorticity vector ($\tilde{\omega}$). Physically, an increase of PV occurs when the heating gradient is positively aligned with the vorticity vector as it is usually the case in the eyewall and in rainbands below the level of maximum heating. In these regions, the heating gradient and vorticity vector are pointing up- and radially outward. The third term accounts for the perturbation flux divergence of asymmetric PV, i.e. the azimuthally averaged effect of the PV flux due to the asymmetric parts of the cyclone wind field. The fourth term represents effects of perturbation diabatic heating. The “flux divergence” of asymmetric heating and vorticity is again positive if azimuthal heating gradient perturbations coincide with positive vorticity vector maxima. This is usually the case for areas of isolated convection. In general, the heating terms are sources of PV below the level of maximum heating (i.e. for areas with an upward pointing heating vector). The flux terms containing $v$ are only local sources or sinks, as they redistribute PV and do not generate it when the material rate of change ($dP/dt$) is concerned. The rather complicated nature of friction and its representation in a numerical model makes it difficult to assess the exact role in the total budget. Since this thesis
primarily deals with convective generation of PV, frictional dissipation of PV is of minor
importance here and will not be considered. The results of the PV budget analysis will be
presented for two distinct regions of TCs: 1) inner core/eyewall region and 2) rainband
region beyond ~ 40 km from the core. Figure 4.1 shows horizontal cross sections of PV
(Figure 4.1 (a)) and rain rate (Figure 4.1 (b)) in Rita. The black lines denote the two
regions which have been analyzed separately (eyewall and rainbands).

Figure 4.1. Horizontal cross sections of (a) PV and (b) rain rate in Rita. Black lines
denote inner core and rainband region.

4.1.2 PV budget of the inner core

Generally speaking, PV generation rates in the hurricane eyewall are greatest.
This is not surprising given that the vertical mass transport is largest in this region and
heating gradient and vorticity vector are pointing in the same direction. Figure 4.2 shows
the PV generation rates in Rita (solid red line) and Katrina (solid blue line). According to
the Reynold’s decomposed PV budget equation, two separate panels are shown for both
the contribution of the mean (i.e. azimuthally averaged) diabatic heating term \(-\frac{\bar{q}}{\rho} \overrightarrow{\omega}\) and the perturbation parts \(-\frac{1}{\rho} Q' \overrightarrow{\omega}\). The circularity and symmetry of the eyewall make the contribution of the mean dominant. PV generation rates approach 50 PVU hr\(^{-1}\) in Katrina’s eyewall, which are the highest values found in this analysis. The dashed lines in Figure 4.2 are the azimuthally averaged rain rates of the respective storms (Katrina blue, Rita red). The rain rates are overplotted to indicate the location of the eyewall and rainbands. The solid black line in the plot denotes Rita’s azimuthally averaged radial PV distribution, the dashed black line shows the same for Katrina. Both rain rate and radial PV profile are not drawn to scale but are normalized by some factor in order to fit the scale of the ordinate. All variables in Figure 4.2 are averaged over a period of 6 hours, Katrina from 0300-0900 UTC August 28 and Rita 0800-1400 UTC September 21. Katrina’s PV generation rates exceed Rita’s (Figure 4.2) since the storm is in a period of rapid intensification and the hurricane’s inner core circulation is dominated by the strengthening and contracting eyewall. Inside the main PV generation region between 10 and 15 km, a smaller area of PV depletion can be found in both storms, and we speculate that this region at the inner edge of the eyewall is due to diabatic cooling due to
downdrafts (Willoughby 1998). Figure 4.2 (b) shows the PV generation by the perturbation components of the diabatic heating. The most striking feature in this plot is the PV sink region in the center of the eyewall, with positive values at the edges of the eyewall. Perturbations in the heating field are manifestations of convectively-coupled VRW as was shown in the previous chapters. These eddies thus redistribute PV from the
main generation region downgradient and are part of the PV mixing dynamics described by Schubert (1999). Figure 4.3 displays the same variables for the following 6 hour period (Katrina 1000-1600 UTC August 28, Rita 1500-2100 UTC September 21). It shows the same pattern indicating that the evolution of the two storms is still similar. Katrina has intensifies faster than Rita, indicated by both higher PV generation rates of the azimuthally averaged diabatic heating (Figure 4.3 (a)) and higher PV values in the eye (dashed black line). During the next 6-hour period (1300-1900 UTC August 28 for Katrina and 0000-0600 UTC September 22 for Rita, Figure 4.4), Rita’s primary eyewall weakens significantly from a PV generation point of view. The generation of PV by the
symmetric heating (Figure 4.4 (a), red solid line) has decreased from previous levels, the amount of PV depleted is even larger than the amount generated. This shows that in Rita the EWRC is taking place, the convection in the inner core weakens because of decreasing inflow and inward moisture fluxes. Note that the secondary maximum

Figure 4.4. Same as Fig. 4.2, but from 1300-1900 UTC in Katrina and 0000-0600 UTC 22September in Rita.

in Rita is clearly evident in the rain rate at 40-50 km. In Figure 4.4, Katrina’s values are averaged from 1300-1900 UTC August 28 because the higher temporal resolution data has not been outputted for later periods due to the storm’s uniform evolution. Figure 4.5 depicts the same variables for the period 1200-1800 UTC September 22 in Rita and again 1300-1900 UTC August in Katrina. In Rita (red lines) there is little evidence left of the
original eyewall at 15 km, however the secondary eyewall becomes apparent in both the mean and perturbation PV generation terms at \( \sim 35 \) km radius. The perturbation components now show a similar pattern to that of an eyewall, (see Figure 4.2). This means that the PV generated by the mean heating (Figure 4.5 (a)) is being redistributed mostly inward by the perturbation component (Figure 4.5 (b)).

Figure 4.5. Same as Fig. 4.2, but from 1300-1900 UTC in Katrina and 1200-1800 UTC in Rita.
4.1.3 PV Budget of the rainband region

We will put particular emphasis on the PV generation rates in the rainband region between ~ 50 and 130 km from the center. It is in this region where the secondary ring forms and acquires eyewall characteristics. In general, PV generation rates in the regions farther away from the center are much smaller compared to the eyewall (this was also the case in Figures 3.10 and 3.11, where we used a logarithmic scale to highlight PV in the outer regions). Especially the projection of PV generated by diabatic heating onto the azimuthal mean yields much smaller values than in the inner core. This is due to the decreased amount of symmetry; generally rainbands are less symmetric than the eyewall and have large areas with stratiform precipitation which are not conducive for generating PV on a small scale. The PV generation due to perturbation components is larger at radii beyond 40 km from the center than the mean contributions as opposed to the findings in Chapter 4.1.2 (eyewall region). Figure 4.6 shows the averages over the period from 0300-0900 UTC August 28 in Katrina and 0800-1400 UTC September 21 for Rita. While Katrina’s PV generation by asymmetries in the rainband region does not deviate much from zero between 60 and 120 km, Rita’s PV generation rates are higher in this region, and stay in the positive range (Figure 4.6 (b)). The dashed red and blue lines in Figure 4.6 show that the area of enhanced PV generation in Rita coincides with the rainbands (dashed red: rain rate in Rita, dashed blue: rain rate Katrina). Furthermore, the azimuthally averaged PV profile in Rita features elevated levels (dashed black: PV Katrina, solid black: PV Rita). The PV generation rates are small in comparison with the values in the eyewall (1.5-2 PVU h⁻¹ in Rita’s rainband compared to 40 PVU h⁻¹ in the
eyewall). Figure 4.7 shows the PV generation rates for the period 1000-1600 UTC August 28 in Katrina and 1500-2100 UTC September 21 in Rita.

During this time, Rita’s elevated PV profile (solid black line) becomes more pronounced due to persistent enhanced PV generation mainly by the perturbation diabatic heating and perturbation vorticity. Figure 4.8 shows that the secondary rainband/PV maximum in Rita acquires characteristics of an eyewall from a PV generation point of view on September...
22: the mean component (Figure 4.8 (a)) shows a pronounced narrow peak at 55 km whereas the contribution of

![PV generation due to Mean and Eddy Diabatic Heating](image1)

![PV generation due to Mean and Eddy Diabatic Heating](image2)

Figure 4.7. Same as Fig. 4.6, but from 1000-1600 UTC in Katrina and 1500-2100 UTC in Rita.

the perturbation component to the budget is negative at this distance from the center (cf. Figure 4.2, solid colored lines). This shows that the perturbations are beginning to redistribute PV away from the main generation as opposed to before where most PV was being generated by the perturbation components.
Figure 4.8. Same as Fig. 4.6, but from 1300-1900 UTC in Katrina and 0000-0600 UTC in Rita.
4.1.4 Secondary PV maximum and secondary eyewall formation

One key point of this analysis is to elucidate the difference in convectively generated PV in the inner core and rainband region of both hurricanes to explain Rita’s development of a secondary ring. The contribution of diabatic heating and vorticity perturbations in the rainband region reveal that PV is being produced in an azimuthally averaged sense more effectively in Rita’s rainband region. This fact and the persistence of the principal rainband in Rita together with the axisymmetrization process seem to be a precursor for Rita’s EWRC. To further highlight the differences between the two storms, we will show the differences of PV generation rates in both hurricanes as well as the difference of the azimuthally averaged PV profile and rain rate.

Figure 4.9 shows the difference of PV generation by mean diabatic heating (red line) and perturbation diabatic heating (blue line). The differences are calculated by subtracting the values in Katrina from the ones in Rita. Positive PV generation rates thus show region where the PV generation rates in Rita are higher. The solid black line denotes the difference in PV. Again, positive values mean larger PV values at a given radius in Rita. The dashed black line shows the azimuthally averaged rain rate difference in order to highlight areas where Rita features more active rainbands. PV and rain rate differences are not drawn to scale. It is clearly evident that PV generation rates, the PV profile and the rainrate have a positive maximum between 60 and 120 km. It is in this region where Rita’s rainband is more efficient in generating PV (blue, red lines) which in turn leads to larger PV values (solid black line). The negative area inside of 60 km explains the lack of secondary spiraling rainbands (VRW) in Rita (see Ch. 3).
Figure 4.10 shows the evolution of PV generation rate differences and PV profile differences 6 hours later (1000-1600 UTC in Katrina, 1500-2100 UTC in Rita). Even though the striking maxima in the PV generation rate differences (red, blue) have decreased by some amount, the excess in Rita’s PV (solid black line) is still discernible. The PV generation rates show the 6-hourly averaged instantaneous PV generation differences whereas the PV profile difference also accounts for redistribution processes. Furthermore, once PV is being generated other processes need to act to deplete it (e.g.
friction). Sinks of PV are smaller than sources in convective active regions. But in general, PV generation in Rita is still larger than in Katrina. Figure 4.11 displays 6-hour averages from 1300-1900 UTC in Katrina and 0000-0600 UTC September 22 in Rita. The maximum (PV generation excess in Rita) becomes narrower and more pronounced. This is a clear indication of the formation of a secondary eyewall. Note that all 3 variables follow this trend. A pronounced peak of PV generation by perturbation heating and vorticity can be seen near 40 km. At this radius, the perturbation component PV generation rate in Rita exceeds the one in Katrina by almost 3 PVU hr\(^{-1}\). It
is located inside of the forming secondary eyewall as indicated by the rainrate/PV peak (dashed/solid black line). This behavior shows that the maximum perturbation PV generation rates are found inward from the PV maximum and thus lead to an inward propagation of the secondary PV maximum.

This analysis showed that Rita’s rainband is much more effective in generating PV which projects onto the azimuthal mean. However, this analysis cannot explain why Rita’s rainband is more likely to generate persistently PV through convection at a certain radius.

Figure 4.11. Same as Fig. 4.9, except for averages from 1300-1900 UTC in Katrina and 0000-0600 UTC September 22 in Rita.
Chapter 5

Conclusions

5.1 Summary of Key Results

This study is aimed to better understand the dynamic process of concentric eyewall formation and eyewall replacements in hurricanes, specifically the effects of convectively-generated PV in the rainbands on the formation of secondary eyewalls. High-resolution MM5 model forecasts of Hurricanes Katrina and Rita (2005) and observations from the RAINEX field program were used to investigate the interactions between the hurricane inner core and rainbands in terms of structure changes, in particular the formation of a secondary eyewall as observed in Rita. The model forecasts captured the distinct evolutions of the two major hurricanes over the Gulf of Mexico, namely one with eyewall replacement cycle and one without, which was consistent with the RAINEX observations. This provided a unique opportunity to examine the dynamic and physical processes. Detailed analysis of the storm structure and PV distribution has led to the following conclusions:

(1) Both the model forecasts and observations show distinct patterns of rainbands in the two hurricanes. Rita’s outer rainbands are a clear manifestation of the principal band (Willoughby et al. 1982) which later consolidated into a secondary ring of convection with a moat region between the primary eyewall and the secondary ring. This leads to an enhanced ring of PV and wind velocity, which continues to intensify over time and finally becomes the new eyewall as the old primary eyewall decays. Although Katrina had a similar principle band, it developed active inner rainbands which were
spiralizing between the principle band and the primary eyewall. Unlike Rita, there was not a clear moat region in Katrina.

(2) To examine the dynamic process that may contribute to the formation of the secondary eyewall and eyewall replacement in Rita, analysis of PV distribution and vortex Rossby waves was conducted using the model forecast fields. The rainrate, PV and vertical velocity fields have been decomposed into wavenumber components. Over a period of intensification in Katrina, VRW are active and convectively coupled as both the PV and rainrate field exhibit extrema in their respective wave components. The inner spiral rainbands in Katrina seem to be manifestations of VRW. These rainbands are relatively short lived and thus do not form a secondary ring which is persistent. More importantly, these rainbands are not associated with a secondary maximum in the azimuthally tangential wind speed and thus do not qualify as a secondary eyewall. This maximum was observed with the feature in Rita and so gives evidence that the outer rainband truly formed into a secondary eyewall. The waves form in the inner core region adjacent to the eyewall and propagate outward to a radius of ~70 km. The storm’s PV gradient supports this finding with a vorticity skirt in this region. In Rita the analysis shows a different pattern in terms of VRW activity. During the formation stage of the concentric eyewall structure, VRW activity is limited. The PV gradient is elevated in comparison to Katrina, especially in the outer regions, but lacks radial decrease. Thus the VRW supporting mechanism cannot be found. After the secondary ring becomes more consolidated, an associated radial gradient is supportive of outward propagating VRW. Thus it can be concluded that the concentric eyewall structure formed without interference from VRW in the first place.
A detailed PV budget analysis was conducted to better understand the effects of convectively-generated PV in the rainbands on the formation of the secondary eyewall. It showed that Rita is much more effective in terms of PV generation by convection in the outer rainband region. Our analysis focused on the generation PV projecting onto the azimuthal mean as the azimuthally averaged PV structure is necessary to speak of a true concentric ring. Furthermore Nolan et al. (2007) showed that the response of a TC in terms of intensity change is heavily dependent on the azimuthally averaged forcing, they found that the asymmetric component actually weakens the parent vortex. The PV generation was decomposed into mean and perturbation contribution to the symmetric local rate of change. The inner core PV generation patterns are similar in Katrina and Rita with large rates of convectively generated PV in the eyewall. The effect of eddies (VRW circling around the PV gradient associated with the eyewall) convey PV from the main region of generation into the eye (mixing process) and radially away from the eyewall (PV redistribution). This is consistent with other studies (e.g. Schubert et al. 1999). In the outer region however (beyond 80 km), the heating generated PV rates in Rita exceed the ones in Katrina by up to 100 %. This is a manifestation of the rainband in Rita which is convectively more active, at least in an azimuthally averaged sense. We found most of the induced PV is due to convection because the perturbation components contribute more to the azimuthal PV generation than the azimuthally averaged PV generation. In other words, PV is mainly generated by convective updrafts and then projected onto the azimuthal mean. Physically, this process is attributed to the strong axisymmetrization in a hurricane. The generated PV changes the wind field and generates a jet at the level of maximum heating. This feature has been observed in real storms (citation). HH08
confirmed an updraft-downdraft pattern that has been previously proposed by Barnes et al. 1983. These downdraft transport the momentum associated with the midlevel jet closer to the surface and inward. This process could further strengthen the convective active rainband through enhanced surface fluxes. The strengthening of the rainband and further PV generation plus axisymmetrization could lead to the formation of a secondary eyewall.

Figure 5.1 shows a schematic view of the distinct differences in Katrina and Rita. The colors are the amount of PV being generated by convection (red is Rita, blue Katrina). It also shows the moat in Rita (PV minimum between the two main generation regions: eyewall and principal rainband) and the PV skirt in Katrina supporting outward propagating VRW.

Figure 5.1. Schematic of radial distribution of PV generation rates in Katrina (blue) and Rita (red).
5.2 Future work

This study identified that convectively-generated PV in the rainbands in Rita seems to be responsible for the formation of the secondary eyewall. However, the question remains to be answered as to what the processes are controlling the different rainband structures in Rita and Katrina. Ortt and Chen (2008) suggested that the environmental moisture distribution may a factor in organizing the patterns of rainbands in the two storms. It remains speculative whether and how the relatively dry outer environment and strong moisture gradient surrounding Rita contributed to the ring-like pattern in the rainbands, which led to the formation of the secondary eyewall. Numerical experiments will be designed to explore the sensitivity of rainbands to the environmental moisture distribution so we can further examine the hypothesis proposed in Ortt and Chen (2008). The result could provide some insights for the environmental influence on the hurricane dynamics related to the formation of concentric eyewalls and eyewall replacement cycles, which is critical for forecasting hurricane intensity change.
REFERENCES


