Large-scale influences on tropical cyclogenesis for selected storms in the 2005 Atlantic hurricane season

Jinwoong Yoo
Louisiana State University and Agricultural and Mechanical College

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LARGE-SCALE INFLUENCES ON TROPICAL CYCLOGENESIS
FOR SELECTED STORMS IN THE 2005 ATLANTIC HURRICANE SEASON

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Geography and Anthropology

by

Jinwoong Yoo
B.A. Seoul National University, Korea, 1999
M.A. Seoul National University, Korea, 2003
May 2011
DEDICATION

I dedicate this research first and foremost to my Lord Almighty, Jesus Christ, and the Holy Spirit who have been keeping me from the hard times and have allowed me to complete this study.

I also wish to dedicate this manuscript to my wife, Jiyoon Kim, who supported me wholeheartedly in everything, to my three-year-old daughter, Elizabeth, who kept encouraging me with the question, “Are you doing okay with your paper?”, and my one-year-old son, Isaac, who welcomes me home every night by crawling to me and then standing while holding my legs with a big smile.

My dedication goes to my family members:

Father – Jung Hwan Yoo
Mother – Soon Jeong Ryu
Sister – Eunmi Yoo
Brother – Youngwung Yoo, wife Jungmi Choi, and son Joo-An Daniel Yoo

Also to my other family members:

Father – Hyung Moo Kim
Mother – Yang Ja Kwon
Sister – Meenzee Kim who stayed with us and was of great help to my family and
Brother – Chang Mo Kim.
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Personally, I would like to thank specially my parents for their support and patience with their love for their Little Son, that I know and I feel every moment I talk to them and I will remember forever.
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ABSTRACT

Unpreparedness of large and increasing populations to Atlantic tropical cyclones (TCs) in North and Central America often causes a significant percentage of human casualties and economic losses, which results in part from the difficulty of forecasting tropical cyclogenesis (TCG) and changes in TC track and intensity. Although the mechanisms that lead to TCG have been studied extensively, lack of knowledge still exists about the relative importance of the precursor factors responsible for TCG, especially in the Gulf of Mexico/Caribbean basin where no clear genesis mechanism has been identified for TCs.

A series of studies in this dissertation examines influences of large-scale atmospheric circulation on TCG and intensity change mechanisms for Tropical Storm Arlene and Hurricanes Cindy, Dennis, and Wilma in 2005 by using various derived and observed data sets. To support the main analyses of the large-scale circulations GOES-12 satellite water vapor imagery and the Weather Research and Forecasting (WRF) model (V.3.2.1) are used. Six-hourly NCEP FNL (final) operational global analysis data and daily “real-time global” (RTG) sea surface temperature (SST) data are used as WRF model inputs.

Results show that large-scale, low-level circulations incurred by subtropical high pressure systems in the surrounding ocean basins or triggered by mid-latitude troughs over northeastern North America play critical roles in the TCG process in the western North Atlantic. In particular, the convergence of temporary westerly winds from the eastern North Pacific and the southeasterly/easterly winds from the Atlantic under the orographic effects of Central America creates conditions in the lower atmosphere that favor the development of a meso-scale vortex over the warm sea surface, leading to TCG. WRF model simulation revealed that the interaction between the mid-latitude systems and tropical atmosphere determined the success or failure of
the TCG forecast, which suggests that large-scale, low-level circulations heavily affect TCG and that every large-scale vortex and circulation component in the immediately-neighborhood region of the storm development is important for TCG forecasting. This study shows that the global WRF has a potential to be used for operational short-range TCG forecasting.
CHAPTER 1. INTRODUCTION

According to the U.S. National Hurricane Center’s (NHC) HURDAT database of historical Atlantic basin (including the North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea), an average of 11.3 named systems per year developed during the 1966 through 2009 Atlantic hurricane seasons (1 June – 30 November), 6.2 of which were hurricanes and 2.3 of which were major hurricanes (Category 3 or greater in strength). In 2009, 36.2 million people (approximately 12 percent of the nation’s population) lived in the coastal areas of states from North Carolina to Texas and were therefore threatened by Atlantic hurricanes (http://www.infoplease.com/spot/hurricane-census.html#axzz0yh0Pi2ry). The population in these coastal areas has increased by 158 percent since 1960; About 50 to 100 people lost their lives by hurricanes landfalling along the U.S. coastline in an average three-year period (http://www.infoplease.com/spot/hurricane-census.html#axzz0yh0Pi2ry). Human casualties and economic losses from tropical cyclones (TCs) in Central America and the Caribbean islands are even greater.

Pielke et al. (2008) suggested that during the 1900-2005 period, the average annual damage in the continental U.S. due to TCs was estimated to be approximately $10 billion (normalized to 2005 value) and the most costly years were 1926 and 2005; the most destructive single hurricanes were the 1926 Great Miami storm ($140-157 billion normalized to 2005 dollars) and Katrina in 2005 ($81 billion). The total damage in the U.S. accumulated by the six landfalling 2005 Atlantic TCs (Cindy, Dennis, Katrina, Ophelia, Rita, and Wilma) from among the 28 named storms in that season is estimated to be $114.22 billion combined for Cindy (Stewart, 2006), Dennis (Beven, 2005), Katrina (Knabb et al., 2005), Ophelia (Beven and Cobb, 2006), Rita (Knabb et al., 2006), and Wilma (Pasch et al., 2006).
A significant percentage of the losses incurred by TCs is attributed to the unpreparedness of
the population, which results in part from the difficulty of forecasting tropical cyclogenesis
(TCG) and changes in TC track and intensity. The U.S. National Hurricane Center (NHC) issues
an official TC forecast only for systems with TC properties at both the forecast and the verifying
time; storms at all other stages (e.g., extratropical, tropical wave, remnant low) are excluded
(Franklin, 2006). Thus, no agency is directly responsible for forecasting TCG, leading to
potentially increased danger to lives and property.

Observations in the intertropical convergence zone (ITCZ) have shown that only a few
organized cloud clusters develop into TCs (Simpson and Riehl, 1981). Forecasting which cloud
cluster will develop into a TC is an ongoing research topic. Although previous research
suggested precursor environmental conditions (e.g., Gray, 1968; DeMaria et al., 2001; Davis et
al., 2008) that are favorable to TCG, those conditions have not succeeded in explaining which
processes are key mechanisms that trigger the TCG, leading other environmental conditions to
follow in the TCG process. It seems that sea surface temperature (SST) over 26°C and latitudinal
limitation of more than five degree north or south are fundamental necessary conditions so far.
But the degree of importance and cause-effect relationships among the environmental conditions
remain unknown.

On the other hand, Gray (1998) attempted to provide a step-by-step model of how large-scale
atmospheric motion engages with the TCG so that the environment triggers a meso-scale
convective system (MCS), leading a TCG. Bracken and Bosart (2000) noted that phenomena
such as a low-level cyclonic vorticity maximum, weak vertical shear, persistent and organized
deep moist convection, and perhaps convection-induced moist mid- and upper- tropospheric
conditions are set by the synoptic-scale atmosphere and the details of the interactions between
these synoptic-scale processes and the meso-scale flow will ultimately determine where, when,
and how a warm core vortex forms. But they did not provide the mechanism how the “synoptic scale” atmosphere is set.

Recently, Diedhiou et al. (2010) attributed Atlantic TCG to large-scale precursor conditions, including stronger-than-average “monsoon”-induced winds, lower-than-normal outgoing longwave radiation (OLR) values over west Africa, warmer waters, lower pressure, stronger mid-level humidity, and a higher degree of atmospheric instability in the Atlantic Ocean. However, these narrative, statistical descriptions do not fully address the question of how TCG occurs. While important, the recent work of Diedhiou et al. (2010) falls short of describing a dynamic mechanism that directly produces the persistent convection which is the key to TCG. So the precise TCG mechanism in the North Atlantic Ocean remains somewhat unclear and controversial. No study to date has provided a clear view of the factors responsible for TCG in the Atlantic basin.

HURDAT provides a chronology of points of TCG and tracks by month over the Atlantic Ocean (See images at http://www.nhc.noaa.gov/pastprofile.shtml#ori). A review of these images reveals at least two types of prevailing tracks: One zone of TCG (primarily in June, July, October, and November) is centered on Caribbean Sea, while TCG in the other zone (primarily in August and September) occurs in the central tropical Atlantic – the so-called “Cape Verde” storms. The difference in location may imply different forcing mechanisms of TCG for those two groups. While the genesis of “Cape Verde” TCs has been explained mainly by the influence of (African) easterly wave (Landsea, 1993), no clear genesis mechanism has been identified for the TCs that develop in the Caribbean Sea and Gulf of Mexico.

This study attempts to identify key planetary-scale dynamical mechanisms responsible for the persistent convection in the western North Atlantic and to explain how the large-scale features control western Atlantic TCG. The hypothesis is that TCG begins with the interaction of two or
three planetary-scale atmospheric circulations. These circulations may include prevailing lower-tropospheric airflows characterized by their own flow directions, flow speeds, and humidities over the characteristic terrain of Central America. The confluence of these air masses initiates vortex development and creates persistent convection over the warm water near the ITCZ that eventually generates a TC.

Figure 1.1. Best tracks of the four TCs with their major intensity change locations and times (mm/dd/UTC). Tropical Storm Arlene (green), Hurricanes Cindy (orange), Hurricane Dennis (blue), and Hurricane Wilma (red). TD: Tropical Depression; TS: Tropical Storm; H: Hurricane; Low: Low pressure; ET: Extratropical cyclone.
To test the hypothesis, three case studies for four TCs (Tropical Storm Arlene, Hurricanes Cindy/Dennis, and Wilma) (Figure 1.1) are conducted. Each case study includes analyses of the large-scale atmospheric and sea surface temperature conditions provided by various data sets. The Weather Research and Forecasting (WRF) model is used to simulate the atmospheric conditions for each case study at smaller spatial resolution than the available NNR data provide. Although model physics are almost identical among the three cases of WRF simulations, model settings differ significantly. Tropical Storm Arlene is simulated at the synoptic scale, the WRF runs for Hurricanes Cindy and Dennis are a hemispheric and a global scale simulation, and only the global simulation setting is used in the WRF simulations of Hurricane Wilma.

Several meteorological scales of analysis are used in this study. “Meso-scale” is a term that conventionally is considered to range in size from several kilometers to about several hundred kilometers, while “synoptic-scale” is larger than meso-scale but within a “conceptual” region. Although “large-scale” often refers to synoptic-scale in meteorological convention, “large-scale” in this study is used for the scale that exceeds one conceptual region. “Planetary-scale” is used here for analysis that is larger than “large-scale”.

This dissertation is composed of seven chapters. The next chapter reviews the literature on general theories of TCG mechanisms. Then three case studies of Tropical Storm Arlene (2005), Hurricanes Cindy and Dennis (2005), and Hurricane Wilma (2005) are described in the next three chapters, respectively. A summary of findings and conclusions from the three case studies will follow in the final two chapters, respectively.

1. References


CHAPTER 2. LITERATURE REVIEW

While tropical cyclogenesis (TCG) is still poorly understood (Molinari et al., 2000), emphasis in TCG mechanism research has been placed on the importance of the monsoon trough (Gray, 1968; McBride and Keenan, 1982; Zehr, 1992), air-sea interaction (Emanuel, 1986, 1989), scale interaction (Holland, 1995), vortex interaction (Ritchie and Holland, 1993; Harr et al., 1996; Simpson et al., 1997), ITCZ breakdown (Ferreira and Schubert, 1997), monsoon confluence (Holland, 1995; Briegel and Frank, 1997), environmental wind surge with enhanced relative vorticity in the lower troposphere (McBride and Zehr, 1981; Love, 1985a, 1985b; Davidson and Hendon, 1989; Zehr, 1992), influence of the upper-troposphere (Sadler, 1976; Pfeffer and Challa, 1981; Bosart and Bartlo, 1991; Montgomery and Farrell, 1993; Briegel and Frank, 1997; Bracken and Bosart, 2000), topography (Zehnder, 1991), and easterly waves (Burpee, 1972; Molinari et al., 2000). But the precise identification of the sequence of factors triggering the TCG remains largely unknown, though some progress has been made in understanding of vertical wind shear decrease during the development of storm core (Molinari et al., 1995; Davis and Bosart, 2003).

However, most of these ideas of TCG have been constructed by studies focused on the Pacific basin. Use of these features as TCG predictors in the Atlantic basin can be problematic because of the differences in basin size and landmass-ocean distribution. While the monsoon trough is the breeding region of most TCs in the western North Pacific basin, there is apparently no monsoon trough region in the western Atlantic (Chan and Kwok, 1999). Among dynamics-based TCG research for the Atlantic basin, the majority of studies have been conducted over the central tropical Atlantic, focusing on (African) easterly waves, mean vertical shear, vertical instability, and mid-level atmospheric moisture (e.g. Landsea, 1993; DeMaria et al., 2001), and a majority of these studies focus on meso-scale features. The impacts of tropical waves as TCG mechanisms
have been emphasized in Atlantic (e.g. Riehl, 1954) and eastern North Pacific (Molinari et al., 2000) TCG studies. However, TCG mechanisms in the Caribbean Sea and Gulf of Mexico often cannot be fully explained solely by easterly wave features. Despite the differences in TCG mechanisms within the Atlantic basin (western vs. central tropical), and despite the fact that threats by TCs have been increasing in the western Atlantic region continuously recently, little research has investigated the relative roles of specific TCG mechanisms over the western Atlantic basin.

To better understand TCG mechanisms in the Caribbean Sea and Gulf of Mexico, under the premise that meso-scale features that trigger a TCG would be the same if the favorable conditions are met, large-scale features that are characteristic over the western North Atlantic should be considered first. These large-scale regional characteristics include land-ocean distribution, topography of the region, regional characteristics in the interaction between tropical circulation and mid-latitude systems, and the influence of mid-latitude systems in the opposite (southern) hemisphere on TC development in the western North Atlantic. Influences of mid-latitude systems on the TC activities are particularly poorly understood (Holland, 1995).

The indispensible role of large-scale external circulations in TCG is irrefutable, based on numerous persuasive previous studies in the Pacific (e.g. McBride and Zehr, 1981; Briegel and Frank, 1997; Gray, 1998). Bister and Emanuel (1997) have hypothesized that a moist lower to middle troposphere followed by reduction in entrainment effects is necessary for TCG. But in the western Atlantic, convergence in the intertropical convergence zone (ITCZ) does not contribute significantly to moistening the lower troposphere because of the relatively weak vertical motion in general (McBride and Gray, 1980). McBride and Gray (1980) noted that no individual large-scale factor such as the presence of an easterly wave or the ITCZ is solely responsible for organizing tropical convection; but instead a combination of multi-scale forcing mechanisms is
required. As long as the fundamental geophysical conditions for TCG are present, it is the large-scale modifications to the general circulation patterns that make TCG most likely (McBride and Zehr, 1981). Among the large-scale prerequisite conditions for TCG, strong low-level cyclonic horizontal shear and upper-level anticyclonic shear seem to be most important (McBride and Zehr, 1981). Love (1985a, 1985b) showed that cross-equatorial wind surges from the winter hemisphere enhance the low-level cyclonic shear, triggering TCG in the summer hemisphere. Ooyama (1982) added that inflow above the boundary layer is an important prerequisite for TC intensification because the vortex spin-up in that layer is less dissipated by the surface friction, thereby accelerating the vertical displacement of mass from the core to restore gradient balance and lowering central pressure.

In studies of the environmental influences on TC activities, the role of a mid-latitude or extratropical trough has been investigated often. Many TC studies have emphasized the potential influence of an approaching extratropical trough in the upper troposphere several hundred kilometers to the west and north of the storm center on TC intensification within 24 hours prior to minimum central pressure (Molinari and Vollaro, 1989). Merrill (1988) and Molinari and Vollaro (1989) suggested that eddy momentum advection from the trough may intensify a TC, leading to an asymmetric structure of the storm. Following up on the ideas of Pfeffer and Challa (1981) on the role of eddy momentum fluxes in the development of hurricanes, Molinari and Vollaro (1989, 1990) speculated that enhancement of the radial-vertical circulation in response to eddy momentum forcing would spin-up the mid-level air. This in turn introduces a secondary wind maximum (Shapiro and Willoughby, 1982) which leads to an intensification of a storm as the internal processes within a storm core begin to take over; Thus, the eddy momentum flux at a mid-latitude upper-tropospheric trough was considered as a catalyst that stimulates internal instabilities in the TC (Molinari and Vollaro, 1989, 1990).
In a composite analyses of TCs that developed from monsoon troughs over the western North Pacific, Briegel and Frank (1997) hypothesized that eastward-propagating subtropical troughs poleward of the location of TCG support TCG by providing upper-tropospheric vorticity advection, thereby forcing upper-level divergence and uplifting. Briegel and Frank (1997) also highlighted that successfully developing TCs had 850 hPa southwesterly surges in addition to the monsoonal easterly winds approximately 48–72 hours prior to TCG, potentially triggering the low-level convergence and deep uplifting necessary for TCG. Using a global numerical weather prediction model for TCG in the western North Pacific, Chan and Kwok (1999) derived a similar conclusion to Briegel and Frank (1997) regarding the general synoptic-scale features present before TCG. Specifically, they emphasized the relatively important roles of the low-level trade winds and the southwesterly low-level wind surge prior to TCG. Interestingly, however, Briegel and Frank (1997) also found that nongenesis cases have upper-level troughs both to the northwest and the northeast of the TCG region, which complicated the distinction between TCG-triggering and non-TCG-triggering synoptic settings. In examining TC track sensitivity using singular vectors, Peng and Reynolds (2005, 2006) showed that the influx of air from upstream regions of the mid-latitude trough from the northwest reinforces the approaching TC by providing an inward radial wind.

Once the National Centers for Environmental Prediction (NCEP) global model was used for a study of TCG for the 1996 Atlantic hurricane season, potentially critical criteria for TCG were found to be 700 hPa relative vorticity exceeding $4 \times 10^{-5}$ s$^{-1}$ and a closed 1000 hPa circulation (DeMaria et al., 2001). However, use of these criteria for forecasting is likely to produce frequent false alarms (DeMaria et al., 2001). The greatest challenge in TCG prediction seems to be associated with difficulties in representing the large-scale atmospheric condition in modeling forecasts of TCG due to the deficiency in the model physics (Chan and Kwok, 1999). More
specifically, the potential influences of cross-hemispheric planetary circulations and interactions between mid-latitude and tropical flow have been largely ignored due to the limitations of observation and model physics in current modeling skills. Instead, current Atlantic storm monitoring efforts are focused on tropical easterly winds and African easterly wave conditions (DeMaria et al., 2001). Research presented in the next chapters will address these gaps in existing knowledge.

1. References


CHAPTER 3. MULTI-SCALE GEOPHYSICAL DYNAMICS THAT GENERATED TROPICAL STORM ARLENE (2005) IN THE ATLANTIC OCEAN

1. Introduction

The mechanisms that lead to tropical cyclogenesis (TCG) have been studied extensively, but TCG is still poorly understood. Following the reviews on TCG mechanisms by Molinari et al. (2000) and Karyampudi and Pierce (2002), emphasis has been placed on the importance of the monsoon trough (Gray, 1968; Zehr, 1992; McBride and Keenan, 1982), air-sea interaction (Emanuel, 1986, 1989), scale interaction (Holland, 1995), vortex interaction (Ritchie and Holland, 1993; Harr et al., 1996; Simpson et al., 1997), ITCZ breakdown (Ferreira and Schubert, 1997), monsoon confluence (Holland, 1995; Briegel and Frank, 1997), environmental wind surge with enhanced relative vorticity in the lower troposphere (McBride and Zehr, 1981; Love, 1985; Davidson and Hendon, 1989; Zehr, 1992), influence of the upper-troposphere (Sadler, 1976; Pfeffer and Challa, 1981; Bosart and Bartlo, 1991; Montgomery and Farrell, 1993; Briegel and Frank, 1997; Bracken and Bosart, 2000), topography (Zehnder, 1991), and easterly waves (Molinari et al., 2000).

However, most of these ideas of TCG have been constructed by studies mainly for TCG over the Pacific basin. In the Atlantic basin, the majority of studies on TCG have been conducted over the central tropical Atlantic basin focusing on (African) easterly waves, mean vertical shear, vertical instability, and mid-level atmospheric moisture (e.g. Landsea, 1993; DeMaria et al., 2001). Especially, the impacts of the tropical waves were much emphasized in the TCG studies over the Atlantic (e.g. Riehl, 1954) and even over the eastern North Pacific (Molinari et al., 2000). To a certain degree, this emphasis seems justified because such “Cape Verde” hurricanes can be disastrous in the Atlantic basin (Landsea, 1993). However, TCG mechanisms in the Caribbean Sea and Gulf of Mexico often cannot be fully explained by easterly wave features. Although it is suspicious of the different TCG mechanisms within the Atlantic basin (western vs.
central tropical) and threats by TCs have been increasing in the western Atlantic region continuously recently as seen in the cases of Hurricanes Dennis and Wilma in 2005, less research has investigated the relative roles of specific TCG mechanisms over the western Atlantic basin.

To better understand TCG mechanisms in the Caribbean Sea and Gulf of Mexico, a multi-scale study of geophysical conditions is needed. These large-scale influences on TCG involve the interaction between tropical circulation and mid-latitude systems. Influences of mid-latitude systems on the tropical cyclone activities are particularly poorly-understood (Holland, 1995). Moreover, the influence of mid-latitude systems in the opposite hemisphere on tropical cyclone development in the Atlantic has not yet been studied.

Avila and Brown (2005) documented Tropical Storm Arlene, noting that the cause of the TCG was not understood clearly. They stated that Arlene seemed to have developed from the interaction of the ITCZ and westward-moving tropical waves of unknown origin and characteristics. They provided only limited information about the ITCZ and the tropical waves. In this research, the TCG mechanism of Tropical Storm Arlene (2005) will be examined from multi-scale points of view. The selection of Arlene allows for clarification on genesis of a storm that the National Weather Service has deemed enigmatic (Avila and Brown, 2005).

2. Data and Methods
The “best track” data by National Hurricane Center (NHC) is used as a guideline of the locations and the intensity changes of Arlene. The National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (NNR) 850 hPa data (2.5°x2.5°) (Kalnay et al., 1996) and the NOAA optimum interpolation (OI) ¼ degree daily sea surface temperature (SST) V2 data (Reynolds et al., 2007) are used to show the planetary-scale, low-level atmospheric flow conditions and SST patterns, respectively. Six-
hourly NCEP FNL (final) operational global analysis data (1°x1°) are used as input data to run the WRF model (V.3.2.1) (see Skamarock et al., 2005). The purpose of running the WRF model is to examine the meso- and synoptic-scale dynamic and thermodynamic factors influencing storm development at finer spatial and temporal scales than is available from other datasets. Finally, GOES-12 satellite imagery was obtained from the Earth Scan Laboratory housed at Louisiana State University and used to validate the NNR data and the WRF model output images against the real observation. It should be noted that the accurate hindcasting of pressure drops or maximum wind speed is still a research topic beyond the scope of this study (Table 3.1).

The next section describes Tropical Storm Arlene (2005) from its origin to dissipation using the NNR and OI SST data. Section 4 presents model parameter options used in the WRF simulation. Section 5 will verify qualitatively the analyses of NNR data and WRF model simulations with GOES-12 imagery. Section 6 provides analyses of WRF model output of the dynamic and thermodynamic fields of Arlene from the time of genesis to her development into a tropical storm. Summary and conclusions will follow in the final section.

Table 3.1. Data sets used in Case Study 1.

<table>
<thead>
<tr>
<th>Data</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Centers for Environmental Prediction / National Center for</td>
<td>Review of Large-scale Circulations</td>
</tr>
<tr>
<td>Atmospheric Research (NCEP/NCAR) Reanalysis (NNR) data</td>
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<tr>
<td>National Oceanic and Atmospheric Administration (NOAA) optimum</td>
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<tr>
<td>interpolation (OI) ¼ degree daily SST V2 data</td>
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</tr>
<tr>
<td>NOAA / Oceanic and Atmospheric Research/Earth System Research</td>
<td>WRF model input</td>
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<tr>
<td>Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD)</td>
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<tr>
<td>Interpolated Outgoing Longwave Radiation (OLR) data</td>
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</tr>
<tr>
<td>Six-hourly NCEP FNL (final) operational global analysis data</td>
<td>Verification of data above</td>
</tr>
<tr>
<td>GOES-12 water vapor imagery</td>
<td></td>
</tr>
</tbody>
</table>
3. Tropical Storm Arlene

a) Easterly Wind Condition

According to the best track data of NHC, Arlene became a tropical depression on 8 June, upgraded to a tropical storm on 9 June and died on 13 June. Because 850 hPa vortex centers in the NNR streamline analysis correspond well with the centers of high and low sea level pressure (SLP), 850 hPa streamlines are superimposed on NOAA OI SST V2 data without showing the SLP (Figure 3.1).

The subtropical high pressure system in the North Atlantic (aka: Azores/Bermuda High) became well-organized in late May, creating a strong easterly wind over the western tropical Atlantic, while wind in the South Atlantic had become vigorous after mid-May. The Azores/Bermuda High continued to generate a strong easterly wind in the Caribbean Sea until 5 June, when it suddenly became disorganized and weakened substantially. However, a continuously strong wind surge from the South Atlantic remained over Brazil with circulation from the South Atlantic through northern South America into the western Caribbean Sea from 8 June (prior to Arlene’s TCG) until she died after landfall on 12 June (Figure 3.2).

![Figure 3.1. A sample of 850 hPa streamline analysis superimposed on SLP (left) and SST (right) contour map 0000 at UTC 8 June. Dot shades enclosed by green and red contour lines represent large-scale wind surges with wind speed exceeding 10 m s⁻¹.](image)
Figure 3.2. 850 hPa streamline analyses superimposed on SST during pregenesis of Arlene (2005). Dot shades enclosed by red contour lines represent large-scale wind surges exceeding 10 m s\(^{-1}\).
b) Low-level Westerly Wind Generation in the East Pacific

While the vigorous Azores/Bermuda high was advecting a strong 850 hPa easterly wind over the Caribbean until 5 June, a low-level cyclonic vortex had begun to build over Panama and western Colombia beginning around 27 May, which triggered a development of westerly winds in the East Pacific. However, the evolution of the low-level westerly winds that influenced the genesis of Arlene was more complicated.

On 29 May, a low-level cyclonic vortex over Panama impacted the downstream flow, generating a anticyclonic vortex to the southwest of it, which was also affected by the existence of the Southeast Pacific high pressure system farther south (Figure 3.3). On 31 May, a wind stream from this low-level anticyclone contributed to the formation of another anticyclone near the center of the warm sea surface around (10⁰N, 100⁰W). While those three low-level vortices interacted each other, the two low-level anticyclones merged on 1 June, with the new anticyclonic center near (0⁰N, 90⁰W). With the support of winds from Northeast Pacific high and Southeast Pacific high, the merged anticyclone expanded on 2 June to become a formidable low-level anticyclone in the East Pacific. It generated a strong westerly wind from the middle of the tropical eastern Pacific (5-10⁰N) to the Caribbean Sea, where it converged with the southeasterly wind from the South Atlantic and the easterlies from the North Atlantic basin. This convergence appears to have generated a prominent meso-scale, low-level cyclonic vortex with its center hovering over Panama after 4 June, setting the stage for Arlene over the Caribbean area. Although the easterly wind weakened on 5 June as noted earlier, the vortex remained over the western Caribbean Sea with an elongated northwest-to-southeast shape, covering the whole Caribbean Sea, with its center near the eastern coast of Nicaragua on 6 June. The westerly wind strengthened once more on 6 June and then weakened somewhat on 7 June, while the southeasterly flow remained.
On the day prior to TCG (7 June), no evidence of a wind surge within 1000 km of the potential center of the storm vortex over Honduras existed, except a southerly surge over the Yucatan peninsula associated with a mid-latitude cyclone developing over the central U.S. and a local high pressure system over the Gulf of Mexico (Figure 3.4).

Figure 3.3. Evolution of low-level meso-scale vortices over the East Pacific created a westerly wind, resulting in a confluence region in the Caribbean Sea. 850 hPa streamline analyses are superimposed on SSTs. Dot shades enclosed by red contour lines represent large-scale wind surges exceeding 10 m s⁻¹.
Figure 3.3. Continued

Figure 3.4. Vortex growth and the genesis of Tropical Storm Arlene.
c) Environmental Wind Conditions on the Genesis Day

At 0000 UTC 8 June, the major wind streams associated with the disturbance were coming from South America and the central tropical Atlantic of South Atlantic origin (Figure 3.5). The wind speed increase over Haiti seems to be related to regional high pressure near the east coast of the United States. No other strong wind surge existed near the vortex center over Honduras. The disturbance became a tropical depression at 1800 UTC 8 June.

When the tropical depression strengthened to a tropical storm on the map of 0600 UTC 9 June, however, Arlene was surrounded by several strong wind regimes: a westerly wind from the East Pacific, a southeasterly wind from the South America, and a southerly flow over the Yucatan peninsula. These conditions were ideal to augment the preexisting meso-scale vortex by advecting angular momentum from every direction evenly. The large wind surges over Brazil and an axis of elongated winds over the Central U.S. are notable. More detailed results will be provided in the three-dimensional analyses of the WRF model output for Arlene.

4. Weather Research and Forecasting (WRF) Model Description

The model microphysical schemes are configured following the NCAR Advanced Hurricane WRF (AHW) microphysics guidelines, including i) the Lin et al. (1983) cloud microphysics scheme; ii) the Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation (Mlawer et al., 1997); iii) the Dudhia (1989) scheme for shortwave radiation; iv) the Yonsei University planetary boundary layer (PBL) parameterization; v) the Monin-Obukhov scheme for the surface layer option; vi) the thermal diffusion scheme for the land surface physics; and vii) Kain-Fritsch (new Eta) scheme for the cumulus parameterization only for the 30 and 10 km resolution domains (Gilliland and Rowe, 2007) (Table 3.2).
Figure 3.5. 850 hPa streamline analyses superimposed on SST during the genesis of Arlene (2005). Dot shades enclosed by red contour lines represent large-scale wind surges exceeding 10 m s$^{-1}$. 
Table 3.2. Physics options implemented in the WRF model simulation.

<table>
<thead>
<tr>
<th>Physics options</th>
<th>Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>The Lin et al. (1983) cloud microphysics scheme</td>
</tr>
<tr>
<td>Longwave radiation</td>
<td>The Rapid Radiative Transfer Model (RRTM) scheme</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>The Dudhia (1989) scheme</td>
</tr>
<tr>
<td>Boundary layer option</td>
<td>The Yonsei University planetary boundary layer (PBL) parameterization</td>
</tr>
<tr>
<td>Surface layer option</td>
<td>The Monin-Obukhov scheme</td>
</tr>
<tr>
<td>Land surface physics</td>
<td>The thermal diffusion scheme</td>
</tr>
<tr>
<td>Cumulus parameterization</td>
<td>Kain-Fritsch (new Eta) scheme (applied only for the domains larger than 10 km resolution)</td>
</tr>
</tbody>
</table>

The five nested grid domains have (x, y) dimensions of 232 × 199 (d01), 286 × 262 (d02), 292 × 322 (d03), 250 × 115 (d04), and 280 × 100 (d05). The largest domain (d01) has a grid size of 30 km and the finest domain has a grid size of 3.333 km. The d02, d04, and d05 domains have 10 km grid size (Figure 3.6). The 38 sigma (σ) level set of Kieu and Zhang (2008) was applied. The model “top” is defined at 50 hPa. To capture the large-scale vortex development, a fixed-domain configuration was used. The simulation model runs from 0000 UTC 7 June, about 42 hours before the best track began, to 0000 UTC 12 June, about 6 hours after the landfall of the storm – a duration of 120 hours.

A preliminary WRF model run for Arlene showed that the storm track forecast deviated to the east compared to the NNR data and the best track analysis due to error propagations from the lateral boundary conditions (LBCs), changing the meso-scale vortices as quickly as 18 hours from the model initialization. To reduce the negative impacts of the LBCs, usually the lateral boundaries are set sufficiently far from the area of meteorological interest (Warner et al., 1997). However, because it becomes so costly to set the lateral boundaries sufficiently far in this case, the WRF model is initialized every six hours and each run extends only for 12 hours, alternatively. The process repeats for the entire model run. Then, only the WRF output of the latter half of each 12-hour run is collected and concatenated for the entire model span (Table
This “step-wise” practice allows the model a six-hour “spin-up” to permit the development of meso-scale structures that are relevant to the large-scale and local forcing and simultaneously to utilize only the forecasts during which meso-scale atmosphere is stabilized (Weiss et al., 2008). Since the model initializes every six hours with the NCEP FNL data including SST, the SST is “virtually” updated every six hours into the model integration.

5. WRF Model Verification with GOES-12 Satellite Imagery

In Figure 3.7, the NNR data and the WRF model simulation are compared to GOES-12 satellite Channel-3 water vapor imagery. Note that there is a 15-minute difference between the GOES-12 imagery and the NNR data. Generally, GOES-12 imagery corresponds well with the NNR wind vectors and wind surge contours (exceeding 10 m s⁻¹).

Figure 3.6. WRF model domains for Tropical Storm Arlene (2005). The nested domain is labeled as d02, d03, d04, and d05. The six-hourly best track locations of Arlene are presented with red dots and lines. Annotations beside the track show the date and hour (DD/HH).
Streamline analysis of WRF model output shows strong agreement with those of NNR data. Wind conditions at the time of model integration are also presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to purple (0 – 46 m s⁻¹). The cloud distribution represented by the iso-surface plots of WRF model output shows good similarity with that of GOES-12 imagery.

Although six-hours of spin-up does not seem to fully stabilize the meso-scale atmosphere (not shown), comparisons of the step-wise WRF model output to GOES-12 and to NNR data reveal that the step-wise practice reproduces significantly accurate results in terms of the atmospheric dynamics.
Figure 3.7. Comparison between GOES-12 imagery (top) and WRF output (bottom) at about 0000 UTC 9 June (left) and 11 June (right). Tropical Storm Arlene reached its maximum intensity at 0000 UTC 11 June. In the GOES-12 imagery plot, wind data from NCEP/NCAR reanalysis are represented with red arrows, and green contour lines represent large-scale wind surges with wind speed exceeding 10 m s\(^{-1}\). A color scheme was used to highlight the high clouds with low temperature. In the WRF model output plots, the iso-surface is depicting three-dimensional cloud distribution. Cloud towers represent strong convection on the surface. Wind conditions at the time of model integration are also presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to purple (0–46 m s\(^{-1}\)).
6. Analysis of WRF Model Simulation

a) Orographic Effect in Vortex Development

As seen in the NNR data, the orographic effects on the lower-level airflow by the Northern Andes Mountains are clearly reproduced in the WRF model simulation (Figure 3.8). Breaks in the wind surges from South America to the north through Colombia allowed for convergence with the easterly wind over the Caribbean Sea, generating meso-scale vortices. In the meantime, three low areas below 500 meters (Salina Cruz at Gulf of Tehuantepec in Mexico, Lake Nicaragua, and Panama) in Central America served as main air channels while the other highlands block low-level airflow in the highland region that easily exceeds 1.5 km (approximately 850 hPa) (Figure 3.9). Also, due to the funneling effect of the highlands, relatively stronger wind is generated near the channels, which strengthened the westerly winds in the Caribbean Sea at the time of Arlene’s TCG.

Figure 3.8. Orographic influence on the low-level circulation is clearly depicted in the low-level wind stream at 500 m (left) and 1500 m (right) plots over the WRF model domain at 1801 UTC 8 June. Low-level westerly winds from the eastern Pacific flow into the Caribbean Sea through the lower elevations over Lake Nicaragua and Panama. A meso-scale low-level cyclonic vortex is developing when the westerly winds meet easterly (or southeasterly) winds in the Caribbean Sea. The vortex becomes the center of a tropical depression. Notice also that the westerly winds result from the interactions between the northeast and southeast Pacific subtropical highs.
Figure 3.9. Synoptic-scale low-level wind and moisture distribution. Two strong influxes into the center of Arlene are coming from the East Pacific and South America. Mixing ratio exceeding 18 g kg$^{-1}$ is represented in red-pink, superimposed by 850 hPa wind. Note that distribution pattern of the high mixing ratio resembles a triangle over the Central America. Arlene’s vortex center remained near the northern vertex of the triangular area of the high mixing ratio.
b) Development of Arlene with Synoptic-scale Surface Moisture Advection

In contrast to Avila and Brown’s (2005) emphasis on the pivotal role of a westward-moving tropical wave, westerly winds from the eastern Pacific past Lake Nicaragua significantly contributed to the development of Arlene from the early stage as did the southeasterly winds from South America. Two strong low-level wind streams were persistently present into the center of Arlene: one coming from the East Pacific and one from South America (Figure 3.9). These consistent winds were accompanied by heavy moist air due to the warm SST of the East Pacific and the Caribbean Sea. The geographical distribution of mixing ratios exceeding 18 g kg\(^{-1}\) (red-pink) resembles a triangle over Central America (Figure 3.9). Arlene’s vortex center remained near the northern vertex of the triangular area of this high mixing ratio as it migrated northward, and the moist air within the triangular region flowed into Arlene during its development until Arlene reached its maximum wind speed at 0600 UTC 11 June. After Arlene had been isolated from the triangular region, it began to weaken.

c) Upper-level Wind

A persistent 250 hPa anticyclonic flow existed over the northeast Pacific to the west of Mexico during the period of Arlene, which seems to be related to the mid-latitude upper-level jet stream. The upper-level anticyclone pulled a branch of the jet stream southward over Central America, producing a tropical upper-tropospheric trough (TUTT) (Sadler, 1976; Gray, 1998). WRF model output shows clearly that Arlene’s development was closely associated with the presence of this TUTT (Figure 3.10). During the life span of Arlene, the general upper-level wind pattern remained consistent. However, it is notable that the TUTT underwent a deformation to a certain degree as Arlene advanced northward into the Gulf of Mexico. The northward movement of Arlene also modified the downwind side of the TUTT.
Figure 3.10. 250 hPa wind pattern is superimposed on the iso-surface image of clouds. The cloud tower under the TUTT represents the location of Arlene. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to purple (0 – 46 m s⁻¹).
7. Summary and Conclusions

Multiple-scale atmospheric and oceanic conditions of the western Atlantic basin were analyzed for Tropical Storm Arlene in 2005 to clarify the mechanisms responsible for the TCG, using NCEP/NCAR reanalysis data, NOAA optimum interpolation (OI) ¼ degree daily SST V2 data, GOES-12 satellite imagery, and WRF model (V.3.2.1) with six-hourly NCEP FNL (final) operational global analysis data as model input. Under the large-scale influences from the eastern North Pacific, eastern South Pacific, North Atlantic, and South Atlantic, complicated interactions among low-level vortices in the tropical East Pacific region generated the “temporarily consistent” westerlies from the warm eastern Pacific into the Caribbean Sea for about two weeks before the Arlene developed. Considering that the Madden-Julian Oscillation (MJO) (Madden
and Julian, 1994) was not active in June 2005 (Bell et al., 2006), this dynamic mechanism of westerly wind development in the East Pacific raises a question about the relationship between the MJO and the development of the westerlies (Molinari et al., 1997).

The westerlies from the eastern Pacific and the southeasterlies from the southern hemisphere created a confluence region (Ritchie and Holland, 1999) in the Caribbean, which generated strong positive low-level meso-scale vorticity over the warm sea, leading to a tropical depression at 1800 UTC 8 June. The orographic characteristics of the high terrain with a few spots of low elevation in the Central America played an important role in increasing westerly wind speed via a funnel effect. While an 850 hPa anticyclone east of the U.S. was engaging with the storm from the east and the northeast, the southeast trade winds strengthened the tropical depression into Tropical Storm Arlene at 0600 UTC 9 June, about 150 nautical miles west-southwest of Grand Cayman (Avila and Brown, 2005). Strong moisture advection was provided by the westerlies and southeasterlies to develop Arlene into its maximum intensity. Also the time when Arlene began to weaken seems to be correlated to the time when Arlene became isolated from the intense moisture supply from the low latitude after it advanced far northward into the Gulf of Mexico. The findings in this study are consistent with those by Briegel and Frank (1997) and Chan and Kwok (1999) for the large-scale influences on TCG over the Pacific in that the successful developing TCs had 850 hPa southwesterly surges approximately 48–72 h prior to genesis, potentially triggering low-level convergence and deep uplifting necessary for TCG.

It is noteworthy that the southeast trade wind and the eastern Pacific westerlies are found to be critical in TCG in the western Atlantic basin, at least in the case of Arlene. In particular, the fact that the southeasterly winds from the south Atlantic played a critical role in TCG, which is consistent with the climatological explanations of the anomalously active Atlantic hurricane season in 2005 (Bell et al., 2006), implies that cross-hemispheric planetary circulation may be
more active and important in TCG than previously thought. This result may also suggest that the relationship between TCG and global-scale circulation, including polar activity, is more direct than previously believed. For the purpose of practical application in tropical cyclone forecasting, weather authorities should consider large-scale, low-level circulation and meso-scale vortex development in the East Pacific for improved preparedness for Western Atlantic tropical cyclones. Further broad-scale modeling is needed to clarify the pole-to-tropical interaction and its impact on TCG.

8. References


CHAPTER 4. PLANETARY-SCALE ATMOSPHERIC CIRCULATION AND TROPICAL CYCLONE ACTIVITY IN THE WESTERN ATLANTIC: CASE STUDY OF HURRICANES CINDY AND DENNIS IN 2005

1. Introduction

During the 1900-2005 period, the average annual damage in the continental U.S. due to tropical cyclones (TCs) was estimated to be approximately $10 billion (normalized to 2005 value) and the most costly years were 1926 and 2005; the most destructive single hurricanes were the 1926 Great Miami storm ($140-157 billion normalized to 2005 dollars) and Katrina in 2005 ($81 billion) (Pielke et al., 2008). The total damage in the U.S. accumulated by the six landfalling 2005 Atlantic TCs – Cindy (Stewart, 2006), Dennis (Beven, 2005), Katrina (Knabb et al., 2005), Ophelia (Beven and Cobb, 2006), Rita (Knabb et al., 2006), and Wilma (Pasch et al., 2006) - from among the 28 named storms in that season is estimated to be $114.22 billion.

A significant percentage of the losses incurred by TCs is attributed to the unpreparedness of the population, which results in part from the difficulty of forecasting tropical cyclogenesis (TCG) and changes in TC track and intensity. The U.S. National Hurricane Center (NHC) issues an official TC forecast only for systems with TC properties at both the forecast and the verifying time; storms at all other stages (e.g., extratropical, tropical wave, remnant low) are excluded (Franklin, 2006). Thus, no agency is directly responsible for forecasting TCG, leading to potentially increased danger to lives and property.

Many factors have been studied to understand TC activities, including sea surface temperature (SST), vertical wind shear, vertical instability, mid-level moisture variables, air-sea interactions, meso-scale convective vortices, wind surges, environmental interactions, etc. (e.g. Gray, 1968; DeMaria et al., 2001). But the precise identification of the sequence of factors triggering the TCG remains largely unknown, though some progress has been made in understanding of
vertical wind shear decrease during the development of storm core (Molinari et al., 1995; Davis and Bosart, 2003).

Once the National Centers for Environmental Prediction (NCEP) global model was informally used for a study of TCG for the 1996 Atlantic hurricane season, potentially critical criteria for TCG were found to be 700 hPa relative vorticity exceeding $4 \times 10^{-5}$ s$^{-1}$ and a closed 1000 hPa circulation (DeMaria et al., 2001). However, use of these criteria for forecasting is likely to produce frequent false alarms (DeMaria et al., 2001).

The greatest challenge in TCG prediction seems to be associated with difficulties in representing the large-scale atmospheric condition in modeling forecasts of TCG due to the deficiency in the model physics (Chan and Kwok, 1999). More specifically, the potential influences of cross-hemispheric planetary circulations and interactions between mid-latitude and tropical flow have been largely ignored due to the limitations of observation and model physics in current modeling skills. Instead, current Atlantic storm monitoring efforts are focused on tropical easterly winds and African easterly wave conditions (DeMaria et al., 2001).

Meanwhile, the mid-latitude trough associated with the polar front jet stream is well-known to support low-level convection. The upper-tropospheric potential vorticity (PV) field has been used frequently to diagnose quantitatively the propensity for storm development within the mid-latitude trough (Palmer et al., 1998). Utilizing singular vector analyses, Palmer et al. (1998) showed that mid-latitude instability is “sensitive” to the region where the latitudinal PV gradient is minimized to the south of the maximum PV anomalies.

On the other hand, in studies of the environmental influences on TC activities, the role of a mid-latitude or extratropical trough has been investigated often. Many TC studies have emphasized the potential influence of an approaching extratropical trough in the upper troposphere several hundred kilometers to the west and north of the storm center on TC
intensification within 24 hours prior to minimum central pressure (Molinari and Vollaro, 1989). Merrill (1988) and Molinari and Vollaro (1989) suggested that eddy momentum advection from the trough may intensify a TC, leading an asymmetric structure of the storm. Following the ideas of the role of eddy fluxes of momentum in the development of hurricanes proposed by Pfeffer and Challa (1981), Molinari and Vollaro (1989, 1990) speculated that enhancement of the radial-vertical circulation in response to eddy momentum forcing would spin-up the mid-level air, which in turn introduces a secondary wind maximum (Shapiro and Willoughby, 1982), leading to an intensification of a storm as the internal processes of a storm core begin to take over. Thus, the eddy momentum flux at a mid-latitude trough in the upper troposphere can be considered a catalyst that stimulates internal instabilities in the TC. In examining TC track sensitivity using singular vectors, Peng and Reynolds (2005, 2006) showed that the influx of air from upstream regions of the mid-latitude trough from the northwest reinforces the approaching TC by providing an inward radial wind.

However, the utility of quantifying the impact of the eddy momentum flux in TCG for forecasting purposes is limited at present because of the difficulty in acquiring the upper tropospheric rawinsonde data. The relationship between the eddy momentum flux and the ultimate intensity change estimated at the surface also remains unknown (Molinari and Vollaro, 1989).

The purpose of this study is twofold: 1) to infer large-scale precursors to TCG in the western Atlantic basin for Hurricanes Cindy and Dennis; and 2) to test how the Weather Research and Forecasting (WRF) model (version 3.2.1) (see Skamarock et al., 2005) performs in TCG simulation within two different configurations of model domain: one is a hemispheric region and the other is a global domain. Results of the two simulations are compared. Two planetary-scale low-level atmospheric circulations are investigated as possible precursors to TCG and TC
intensity change: southeasterly winds from the southern Atlantic and PV anomalies in the upper-level trough in the subpolar and mid-latitude low pressure systems over the North America.

2. Data and Methods
The “best track” data by NHC is used as a guideline of the locations and the intensity changes of Cindy and Dennis. Large-scale SST patterns are described using the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) ¼ degree daily sea surface temperature (SST) V2 data which include *in situ* SST measurements from ships and buoys, satellite observations from Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) sensor on National Aeronautics and Space Administration (NASA) Aqua satellite and NOAA 17/NOAA 18 Advanced Very High Resolution Radiometer (AVHRR), and NCEP sea ice data (Reynolds et al., 2007).

The NCEP/National Center for Atmospheric Research (NCAR) Reanalysis (NNR) data (Kalnay et al., 1996) are used show the large-scale wind pattern during the development of Cindy and Dennis. The NNR dataset includes pressure level variables in 17 vertical layers on a global 2.5 by 2.5 degree grid. Hennon and Hobgood (2003) noted that NNR data are superior to the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis data set in the tropics. Daily and long-term mean interpolated Outgoing Longwave Radiation (OLR) data provided by the NOAA / Oceanic and Atmospheric Research / Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD), Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ (Liebmann and Smith, 1996) are used to produce daily OLR anomalies which represent strong surface convection evidently.

To run the WRF model for Hurricanes Cindy and Dennis, six-hourly NCEP FNL (final) operational global analysis data (1⁰x1⁰) and daily “real-time global” (RTG) SST data are used
for three dimensional input data and for SST update, respectively. The model run is set to update SST every six hours into the model integration. The FNL data for this study are obtained from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at NCAR. The original data are available from the RDA (http://dss.ucar.edu) in dataset number ds083.2. The RTG SST data are available from National Weather Service at ftp://ftp.polar.ncep.noaa.gov/pub/history/sst/. The purpose of running the WRF model is to examine the synoptic-scale dynamic and thermodynamic factors influencing storm development at finer spatial and temporal scales than is available from other datasets (Table 4.1).

Table 4.1. Data sets used in Case Study 2.

<table>
<thead>
<tr>
<th>Data</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (NNR) data</td>
<td>Review of Large-scale Circulations</td>
</tr>
<tr>
<td>National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) ¼ degree daily SST V2 data</td>
<td></td>
</tr>
<tr>
<td>NOAA / Oceanic and Atmospheric Research/Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD) Interpolated Outgoing Longwave Radiation (OLR) data</td>
<td></td>
</tr>
<tr>
<td>Six-hourly NCEP FNL (final) operational global analysis data</td>
<td></td>
</tr>
<tr>
<td>Daily “real-time global” (RTG) sea surface temperature (SST) data</td>
<td>WRF model input</td>
</tr>
</tbody>
</table>

3. Hurricanes Cindy and Dennis in 2005

Hurricane Cindy developed on 3 July 2005 in the western Caribbean Sea in a similar location where Tropical Storm Arlene had formed on 8 June 2005. While Cindy was strengthening into a tropical storm, the TCG process of Hurricane Dennis began on 4 July 2005 in the eastern Caribbean Sea. Dennis drifted westward, intensifying rapidly (37 hPa in 24 hr) into a Category 4 hurricane over the central Caribbean – an unusual occurrence of a major hurricane in early July.
(Beven, 2005). Cindy caused one fatality in the U.S. (Stewart, 2006) while Dennis directly caused 42 deaths (22 in Haiti, 16 in Cuba, 3 in the U.S., and 1 in Jamaica) (Beven, 2005). Total U.S. damage incurred by Cindy and Dennis was estimated to be $320 million and $2.23 billion, respectively (Stewart, 2006; Beven, 2005).

TC reports from the NHC for Cindy (Stewart, 2006) and Dennis (Beven, 2005) provide good sources of descriptive meso-scale information, including the storms’ tracks and intensity changes. But the absence of discussion of interactions between the large-scale environment and the hurricanes in these reports and elsewhere complicates efforts to understand the dynamic mechanisms of TCG and rapid intensification that the two hurricanes had shown in the relatively early hurricane season.

In the Atlantic basin, rapid intensifications (Holliday and Thompson, 1979) and “explosive deepening” (Jordan, 1961) of a TC often occurred within 24 hour or even 12 hour before landfall although when the outer bands would start to be deformed by the dry land effects (Babin, 2004). The frequency of near-landfall intensification was higher in the Gulf of Mexico than other areas of the Atlantic basin (Babin, 2004). The fact that a TC can intensify rapidly near its landfall suggests that large-scale factors may play an important role in the intensity change of TCs in the western Atlantic basin.

4. Large-scale Sea Surface Temperature Conditions

During the periods of Cindy and Dennis, SST in the entire western Atlantic basin and central tropical Atlantic was over the 26°C climatological threshold for TC development (e.g. Gray, 1968), with western Atlantic SST peaking at over 29°C (Figure 4.1). The general SST condition over the western Atlantic was warmer than average while the southern Caribbean and central Atlantic had even stronger positive anomalies during 3-10 July 2005 (Figure 4.2).
Figure 4.1. SST over the tropical and western Atlantic during 3-10 July 2005. The thick contour lines are drawn at a 3°C interval and SSTs exceeding 26°C are contoured with dark shades at a 1°C interval.
Figure 4.2. SST anomalies over the tropical and western Atlantic during 3-10 July 2005. Contour lines are drawn at a 1°C interval. Positive anomalies are contoured with dark shades at a 1°C interval and negative anomalies are drawn with dashed line contours.
5. Large-scale Upper-level Atmosphere Potential Vorticity

An upper-tropospheric trough in the Rossby waves (within which the mid-latitude jet stream is embedded) is usually associated with positive PV as shown in Figure 4.3, using a contour interval of 2 PV units (PVU, in $10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$). By convention, 2 PVU is considered to represent the dynamical tropopause (Funatsu & Waugh, 2008). The PV feature embedded within the 200 hPa wind moves sinuously, often merging to evolve into a large-scale trough as at 1200 UTC 5 July (Figure 4.3), and breaks into regional-scale PV anomalies as it travels eastward. On the right hand side of the panel in Figure 4.3, the locations of negative OLR anomalies in the high latitudes represent the lower-level instability regions downstream of the trough. The negative OLR anomaly regions show consistency with the 850 hPa wind surge area. Therefore, it appears that the evolution of Rossby wave propagation, including its interaction with the equatorward atmosphere, determines the regions of strong lower-level convection. Subsequently, the strong surface convection associated with the large-scale Rossby waves triggers synoptic-scale, low-level wind surges in the higher latitudes.

6. Large-scale Low-level Dynamics

At 0000 UTC 1 July, three large subarctic 850 hPa cyclones were situated in the western northern hemisphere: One to the west of the Baffin Island, one over Ontario, Canada, and one between Greenland and Iceland (Figure 4.4a). These cyclones were associated with 200 hPa positive PV anomalies. At the same time, a well-organized subtropical high pressure system in the north Atlantic was producing a substantial 850 hPa easterly wind over the Caribbean Sea, which seemed to be influenced at least indirectly by an orographic effect in South America (Yoo and Rohli, in preparation). By 1200 UTC 2 July, the two westernmost subarctic low pressure systems merged over Hudson Bay and migrated eastward, amplifying the PV over Ontario.
Figure 4.3. Evolution of the distribution of 200 hPa potential vorticity (PVU, shaded) with streamline analysis (left); and negative OLR anomalies (W m$^{-2}$, shaded) with 850 hPa streamline superimposed by the low-level wind surge (right). Contour interval for OLR anomalies is 30 W m$^{-2}$. Areas of low-level wind surges exceeding 10 m s$^{-1}$ are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s$^{-1}$; 1-8 July 2005.
Figure 4.3. Continued.
Consequently, the two cyclones over Ontario and southeast of Greenland became closer to each other even as the center of the cyclone near Iceland moved southeastward toward the United Kingdom (Figure 4.4b). This merger and combined positioning of the subarctic cyclones associated with very high positive PV (>7 PVU) produced a very strong subarctic cyclonic flow over a vast region of northern North Atlantic.

By 1200 UTC 3 July, the strengthened cyclonic flows appear to have intensified the clockwise flow associated with the subtropical high in the North Atlantic and generated an alley of 850 hPa wind surge over inland North America (Figure 4.4c). The result was an elongated region of strong 850 hPa easterly wind in the central tropical Atlantic, which seems to be related to the formation of a broad zone of low pressure that bred Cindy and Dennis a few days later (See OLR anomalies in Figure 4.3).

By 1800 UTC 3 July, the tropical depression that became Cindy had formed about 70 n mi east of Chetumal, Mexico (Stewart, 2006). At that time, the cyclone over the Hudson Strait in northeastern Canada appears to have drawn air from central North America, creating an alley of strong 850 hPa southwesterly winds (Figure 4.3e-f; 4.4c). In turn, air from the Caribbean Sea, crossing the Gulf of Mexico east to west, moved toward interior North America (Figure 4.4c-d). This large-scale low-level circulation seems to contribute to the development of vigorous low-level meso-scale convective vortices (MCVs) (Gray, 1998) over the Gulf of Mexico at the time when Cindy was developing.

Other features of the broad-scale flow reinforced the features that allowed for TCG at the time. Specifically, 850 hPa easterly winds over the Caribbean Sea were accompanied by southeasterly winds from the South Atlantic, creating an anomalously large planetary-scale wind surge over the tropical Atlantic (Figure 4.3f, 4.3h; 4.4c-d). This confluence of the easterly and
Figure 4.4. NCEP/NCAR Reanalysis 850 hPa streamline of wind is superimposed by 200 hPa PV (shaded contour, PVU) over the western part of the northern hemisphere: 1-6 July 2005; areas of low-level wind surges exceeding 10 m s\(^{-1}\) are enclosed by dots within the thick solid contour lines; contour interval is 15 m s\(^{-1}\).
southeasterly winds was directly involved in the genesis of Dennis over the southern Windward Islands at 1800 UTC 4 July (Beven, 2005). Orographic influences over northern South America also seem to have played an important role in the development of MCVs for the TCG of Dennis (Yoo and Rohli, in preparation).

During 4 July, as the subarctic cyclones over the North Atlantic gradually weakened and retreated northward, the winds associated with the north Atlantic subtropical high and the inland low-level air circulation weakened also. Nevertheless, the wind in the Caribbean Sea remained vigorous due to the wind surge from the South Atlantic (Figure 4.3h; 4.4d).

The inland 850 hPa wind surge intensified at 0600 UTC 5 July along the eastern U.S. and Canada, when the depression that became Cindy strengthened into a tropical storm over the central Gulf of Mexico (not shown). Then, the forward speed of Cindy decreased (Stewart, 2006) as a synoptic-scale low-level wind stream was suppressing Cindy’s progress (Figure 4.4e). On 1200 UTC 5 July when the depression that became Dennis became a tropical storm in the eastern Caribbean, the support of a wind surge from Brazil appears to be a critical feature in Dennis’ intensification (Figure 4.4 f-h). This relatively calm low-level condition over interior North America continued at 1800 UTC 5 July (not shown).

According to the best track data, Cindy was only a minimal hurricane, with a wind speed of 65 kt at 0000 UTC 6 July. At that time, a patch of 850 hPa wind surge existed over the eastern U.S. and a mid-latitude high was developing over the U.S central plains, which seems to be associated with the persistent subpolar wind surge over Hudson Bay (Figure 4.4f). By 0600 UTC 6 July, a large-scale 850 hPa meandering airflow had developed over the U.S central plains poleward of Cindy (Figure 4.4g). On the equatorward side of Cindy, low-level outflow from Dennis supported Cindy, along with the southeasterly wind surge from the South Atlantic
(Figure 4.4 f-h). After Cindy weakened to a tropical storm over the Mississippi coast at 0900 UTC 6 July (Stewart, 2006), the large-scale 850 hPa airflow channel weakened also.

At 0000 UTC 7 July, Dennis became a hurricane. Within only 27 hours from that time, he intensified into a Category 4 storm with a maximum wind speed of 120 kt and a central pressure that had dropped by 31 hPa in the previous 24 hours (Beven, 2005). Two large-scale 850 hPa circulations seem to have been involved in this intensification. First, the southeasterly winds became vigorous starting at about 0000 UTC 6 July over inland South America, which seems to be directly related to the orographic effect of the sustained and continuous wind advection from the subtropical high pressure systems in the South Atlantic (Figure 4.4f-h; Figure 4.5a-d). Second, after the eye of Cindy moved inland at 0000 UTC 7 July, a channel of strong southerly 850 hPa wind surges developed from the central U.S. toward the mid-latitude trough again. At this time a more “concatenated-like” line-up of prominent positive PVs occurred from the North Pacific across inland Canada to the North Atlantic and North Sea up to the Arctic Ocean (Figure 4.5).

Additionally, another positive PV anomaly developed over the northeastern U.S. from the Great Lakes area, leading to another development of a low-level wind channel to the east of the PV anomaly (Funatsu and Waugh, 2008). These low-level wind channels along with the remnant low of Cindy over the southeastern U.S. seem to enhance the low-level lateral ventilation of Dennis over the Gulf of Mexico and Caribbean Sea, intensifying Dennis rapidly. The leading edge of the wind surge had retreated northward at 0600 UTC 8 July (Figure 4.5f) while the intensity of Dennis reached a maximum of 130 kt (Category 4) at 1200 UTC on the same day.
Figure 4.5. As in Figure 4.4 but for 7-8 July 2005.
While Dennis maintained a Category 4 hurricane intensity nearly continuously during 8 July, the wind surge region surrounding Dennis covered a large surface from the Caribbean to northeast coast of the U.S. (Figure 4.5f-h). Notably, at this period of major hurricane status, the pattern of the wind surge around Dennis was elongated from south to north while the PV anomaly over the northeastern U.S. was sustaining the low-level wind northward of Dennis. This suggests that the large-scale low-level circulation from the tropics to the mid-latitudes created the low-level condition so that the meso-scale conditions of Dennis could achieve their maximum intensity.

Dennis weakened significantly to 75 kt (Category 1) at 0600 UTC 9 July while it traversed western Cuba (Beven, 2005). During that period, the sub-synoptic-scale wind surge field surrounding Dennis became more circular centered on Dennis, suggesting that Dennis was more likely to be driven by the meso-scale dynamics than the large-scale external environment at that time. However, another channel of low-level wind surge began to form over central North America (Figure 4.6a-b).

Dennis gradually regained its intensity over the Gulf of Mexico, achieving Category 4 status with winds of 125 kt near 1200 UTC 10 July (Beven, 2005). Like the first intensification, this second major intensification was associated with southeasterly winds from South America that were more vigorous than those from the North Atlantic (Figure 4.6a-h). Also, the southern hemisphere subtropical high pressure system located to the east of Argentina contributed to the 850 hPa wind surge across the South American continent (Figure 4.7). The second intensification of Dennis could also have been related to properties of the Loop Current in the Gulf of Mexico, a feature that was not investigated in this study.
Figure 4.6. As in Figure 4.4 but for 9-10 July 2005.
Because the intensities of the southern hemisphere subtropical high pressure systems are dependent on the high southern latitude circulation (Bromwich and Wang, 2008), as in the northern hemisphere subtropical high pressure systems, apparently a relationship between TC activity in the tropical north Atlantic and the circulation mode of the Antarctic seems to exist. This is topic to be investigated in future research. Dennis weakened to Category 3 status with maximum wind speed of 110 kt at 1800 UTC 10 July and made landfall on Santa Rosa Island, Florida, at 1930 UTC 10 July (Beven, 2005).

Figure 4.7. NCEP/NCAR Reanalysis data 850 hPa streamline of wind is superimposed on SST over the western part of the southern hemisphere on 10 July 2005; areas of low-level wind surges exceeding 10 m s⁻¹ are enclosed by dots within the thick solid contour lines; contour interval is 15 m s⁻¹. Shade contours are drawn only for SSTs exceeding 26°C with a 1°C interval.
7. WRF Model Simulation

A WRF model run was executed to examine the process of TCG with improved spatial and temporal resolution, using Hurricanes Cindy and Dennis in 2005 as case studies. Two different model domain settings were implemented: one using a hemispheric region and the other having a global domain. The model microphysical schemes are configured following the NCAR Advanced Hurricane WRF (AHW) microphysics guidelines, including i) the Lin et al. (1983) cloud microphysics scheme; ii) the Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation (Mlawer et al., 1997); iii) the Dudhia (1989) scheme for shortwave radiation; iv) the Yonsei University planetary boundary layer (PBL) parameterization; v) the Monin-Obukhov scheme for the surface layer option; vi) the thermal diffusion scheme for the land surface physics; and vii) Kain-Fritsch (new Eta) scheme for the cumulus parameterization (Gilliland and Rowe, 2007) (Table 4.2).

The 38 sigma (σ) level set of Kieu and Zhang (2008) was applied. The model “top” is defined at 50 hPa. The simulation model runs from 0000 UTC 1 July to 0000 UTC 11 July to include the TCG and the development of Cindy and Dennis – a duration of 240 hours. The model run was set to update SST every six hours into the model integration. The daily “real-time global” (RTG) SST data were interpolated sequentially to produce 6-hourly input data for the WRF run.

For the WRF model simulation in hemispheric domain setting, three nested domain was set. The three nested grid domains have (x, y) dimensions of 241 × 229 (d01), 241 × 229 (d02), 238 × 214 (d03). Each domain has a grid size of 108 km (d01), 36 km (d02), and 12 km (d03), respectively (Figure 4.8). In an effort to minimize the negative impacts of error propagation from the lateral boundary conditions (LBCs) of the model domain, the lateral boundaries are delineated “sufficiently” far from the area of meteorological interest by setting the outermost domain to cover almost a hemisphere (Warner et al., 1997). Only the second domain (d02) is
used for the analysis of WRF model output for the hemispheric domain setting. For the global WRF model simulation, only one global domain was set with \((x, y)\) dimensions of \(721 \times 361\) (d01) (Figure 4.9). The global domain has a grid size of 55.58874 km in the \(x\) and \(y\) directions.

![Figure 4.8. WRF model domain for Hurricanes Cindy and Dennis in 2005. NHC best track was plotted for Cindy (circle with cross) and Dennis (circle filled) with their major intensity changes annotated (See Figure 1.1 for more track information).](image)

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<td>Cumulus parameterization</td>
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8. Analysis of WRF Model Simulation

a) Hemispheric Domain Setting Run

Due to the relatively large outer-most domain size, large-scale circulation patterns in the nested domain of the WRF model were simulated relatively well compared to those of the NNR data at least early period of the WRF run. Interestingly, the high-latitude troughs in the Rossby wave over the northern North Atlantic were reproduced with strong cyclonic circulations as in the NNR data and the development of low-level wind surge alley over inland North America was depicted well prior to the TCG of Hurricane Cindy over the northern Caribbean (Figure 4.10). Also, the confluence of southeasterlies and easterlies to the east of the Caribbean Sea was another example of the realistic simulation. However, the WRF model simulated the development of the inverted “V” wave in the confluence region earlier farther east than it
actually appeared during Dennis in the NNR data. This error resulted in an anomalous eastward shift in Dennis’ track in the model simulation (Figure 4.11). This difference seems to arise from the relatively weak representation of the high-latitude low-level cyclones due to the LBCs. In particular, the simulated cyclone between Greenland and Europe contributed less to the circulation of the subtropical high in the North Atlantic than in reality. Unrealistic input from the LBCs seems to have produced a weaker subtropical high circulation, which in turn produced weaker easterly winds in the low latitudes (Figure 4.3).

Figure 4.10. Realistic reproductions of strong 850 hPa cyclonic circulations over the northern North Atlantic and the development of low-level wind surge alley over inland North America prior to the TCG of Hurricane Cindy over the northern Caribbean.
Although the track of Hurricane Dennis in the WRF model simulation deviated to the east of its actual track, it became clear that the modified large-scale atmospheric circulation due to the LBCs influence the TCG location and its subsequent development. Actually, it seems that the relatively vigorous southeasterly winds from the subtropical high in the South Atlantic determined the TCG location of Dennis in the model simulation. Orographic impacts over Central America also seem to be significant in the TCG process in the WRF simulation.

Figure 4.11. Development of Hurricane Dennis skewed to the northeast of the original development location due to the weakened easterly winds in the WRF model simulation.
b) Global Domain Setting Run

The global WRF model reproduced low-level circulation patterns very closely to those of NNR, especially in the early days of the model integration. The model simulated the passage of the westerly winds from the eastern North Pacific through the low elevations of Central America and their subsequent convergence with southeasterly/easterly winds from the Atlantic (Figure 4.12). The confluence of the westerly and easterly winds seems to be the primary factor contributing to the formation of a meso-scale low-level vortex over the warm sea surface with very humid air. The WRF model also simulated the development of a strong mid-latitude trough over Ontario and its subsequent enhancement of the low-level wind surge alley over the Central United States. Furthermore, the model simulated the low-level wind surge alley that influenced the TCG process of Hurricane Cindy by steering the low-level circulation that was over the northern Caribbean farther west over the Gulf of Mexico (Figure 4.12). However, it seems that the importance of the mid-latitude trough as a cause of the TCG exceeds that of the low-level wind surge alley; the low-level airmass appears to have been pulled northeastward by the mid-latitude trough.

Because the magnification of errors in numerical model simulation across increasing temporal intervals is inevitable, the global WRF model simulation was also affected by the errors as the model integration continued. A noticable error can be found in the confluence area over the central tropical Atlantic between the southeasterly and easterly winds from the subtropical highs in the South Atlantic and in the North Atlantic, respectively, as in the hemispheric model simula-
Figure 4.12. Global WRF model simulation outputs for Hurricanes Cindy and Dennis in 2005. Wind conditions at 1500 m (about 850 hPa) at the time of model integration are presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to blue (0 – 46 m s$^{-1}$). The yellow to purple in the background represent the water vapor in the range of 12 - 20 g kg$^{-1}$. 
Figure 4.12. Continued.
Figure 4.12. Continued.
Figure 4.12. Continued.
tion. The protrusion of the inverted “V” is a remnant of tropical wave that existed in the initial time of the model simulation (not shown). This temporary tropical wave was not treated well in the model simulation. Eventually, this “virtual” existence of the inverted “V” wave affected the downwind region, preventing the development of Cindy as opposed to the result in the hemispheric domain run (Figure 4.13). This error also affected the subsequent development of Hurricane Dennis and its track, triggering earlier TCG and shifting the track to the east, although the extent of the track modification was less severe than the result in the hemispheric domain run. Despite the unsuccessful forecast in Hurricane Cindy, the global WRF model maintained the major large-scale circulation patterns over the North Atlantic fairly well during the rest of the model simulation. It seems that this was possible because the Hurricane Cindy was relatively weak and responsive to larger-scale conditions. This successful global WRF model run outperformed that of the hemispheric domain run of the WRF model in the simulation of Hurricane Dennis.

The global WRF model simulation also showed clearly that the roles of southeasterly winds and the orographic effect over northern South America were significant in the processes of TCG and subsequent intensification of Hurricane Dennis. Without another global WRF model simulation, however, it seems inappropriate to address the relationship between the subtropical high in the South Atlantic and the high-latitude southern hemispheric circulation further in this study. This topic remains for future research.
Figure 4.13. As in Figure 4.12 but for different times.
Figure 4.13. Continued.
Figure 4.13. Continued.
9. Discussion and Conclusion

Bister and Emanuel (1997) have hypothesized that a moist lower to middle troposphere followed by the reduction of entrainment effects is necessary for TCG. But in the western Atlantic, convergence in the intertropical convergence zone (ITCZ) does not contribute significantly to moistening the lower troposphere because of the usually-weak vertical motion (McBride and Gray, 1980). McBride and Gray (1980) noted that no individual large-scale factor such as the presence of an easterly wave or the ITCZ is solely responsible for forming an organized tropical convection; but instead a combination of multi-scale forcing mechanisms is required. As long as the fundamental geophysical conditions for TCG are present, it is the large-scale modifications to the general circulation patterns that make TCG most likely (McBride and Zehr, 1981). Among the large-scale prerequisite conditions for TCG, strong low-level cyclonic horizontal shear and upper-level anticyclonic shear seem to be most important (McBride and Zehr, 1981). Love (1985a, 1985b) showed that cross-equatorial wind surges from the winter hemisphere enhance the low-level cyclonic shear, triggering TCG in the summer hemisphere. Ooyama (1982) noted that inflow above the boundary layer is an important prerequisite for TC intensification because the vortex spin-up in that layer is less dissipated by the surface friction, thereby accelerating the vertical displacement of mass from the core to restore gradient balance and lowering central pressure.

In this study, large-scale atmospheric and oceanic conditions of the western Atlantic basin were analyzed to understand the TCG and intensification mechanism of Hurricanes Cindy and Dennis in 2005, using NCEP/NCAR Reanalysis data, NOAA optimum interpolation (OI) ¼ degree daily SST V2 data, and NOAA/OAR/ESRL PSD Interpolated OLR data. The WRF model was used to simulate the TCG and development of Hurricanes Cindy and Dennis in a hemispheric domain and in a global domain.
During early July 2005, the western Atlantic SST was warmer than the climatological threshold of SST for TCG and the southern Caribbean and central Atlantic were experiencing even stronger positive SST anomalies. It was shown that the synoptic-scale, low-level wind surge in the higher northern latitudes was attributed to the positive PV anomalies in the mid-latitude trough. These anomalies affected the large-scale low-level circulation southward to the tropics, possibly influencing the development of vigorous low-level MCVs due to the topographic effects over the Caribbean Sea when Cindy and Dennis were developing. Specifically, southeasterly winds from the South Atlantic amplified 850 hPa easterly winds over the Caribbean Sea, creating an anomalously large planetary-scale wind surge over the tropical Atlantic. The sequence of development and intensity changes was well-responsive to the development of the low-level wind surge either poleward or equatorward of the storm. The development of the low-level wind surge on the poleward side was related to the mid-latitude trough and that equatorward of the storm was related to the southeasterly/easterly winds. Two WRF model simulations also verified these relationships. The global WRF model simulation also clearly showed that the role of the orographic effect of northern South America was significant in the processes of TCG and subsequent intensification of Hurricane Dennis. The findings in this study are consistent with previous TCG studies in general.

For operational TCG forecasting purposes, the development of lower-level alley of strong 850 hPa southwesterly winds over the central U.S. and 850 hPa southeasterly winds from the South Atlantic seem to be critical precursors to TCG and rapid intensification in the western Atlantic. Thus, monitoring the latitudinal location and strength of the PV anomalies in the mid-latitude trough, the condition of the southeasterly wind surge from the South Atlantic, and the easterlies should all be included in the operational TC forecast. It seems that global numerical model
simulation outperforms regional model simulation in representing the large-scale circulation patterns, which is highly critical in TCG and TC forecast.

10. References


CHAPTER 5. PLANETARY-SCALE LOW-LEVEL CIRCULATION AND THE UNIQUE DEVELOPMENT OF HURRICANE WILMA IN 2005

1. Introduction
The indispensible role of large-scale external circulations in tropical cyclogenesis (TCG) is irrefutable, based on numerous persuasive previous studies (e.g. McBride and Zehr, 1981; Briegel and Frank, 1997; Gray, 1998). In a composite analyses of tropical cyclones (TCs) that developed from monsoon troughs over the western North Pacific, Briegel and Frank (1997) hypothesized that eastward-propagating subtropical troughs poleward of the location of TCG support TCG by providing upper-tropospheric vorticity advection, thereby forcing upper-level divergence and uplifting. Briegel and Frank (1997) also highlighted that successfully developing TCs had 850 hPa southwesterly surges in addition to the monsoonal easterly winds approximately 48–72 hours prior to TCG, potentially triggering the low-level convergence and deep uplifting necessary for TCG. Using a global numerical weather prediction model for TCG in the western North Pacific, Chan and Kwok (1999) derived a similar conclusion to Briegel and Frank (1997) regarding the general synoptic-scale features present before TCG, specifically the relatively important roles of the low-level trade winds and the southwesterly low-level wind surge prior to TCG. Interestingly, however, Briegel and Frank (1997) also found that nongenesis cases have upper-level troughs both to the northwest and the northeast of the genesis region, which complicated the distinction between TCG-triggering and non-TCG-triggering synoptic settings. But, due to limitations in the observational data they could not specify the source of the southwesterly surge into the genesis location, other than any preexisting TCs, which only occur in about 34 percent of all the genesis cases (Briegel and Frank, 1997).

Therefore, there are still some uncertainties in regarding these synoptic-scale features as predictors of TCGs. The confusion partly arises because of a lack of understanding of the circumstances under which the combination of these synoptic-scale features optimizes TCG.
Moreover, use of these synoptic-scale features as TCG predictors in the Atlantic basin can be problematic because of the differences in basin size and landmass-ocean distribution. While the monsoon trough is the breeding region of most TCs in the western North Pacific basin, there is apparently no monsoon trough region in the western Atlantic (Chan and Kwok, 1999).

In a study of Tropical Storm Arlene (2005), Yoo and Rohli (in preparation a) found that low-level vortex dynamics advected temporary low-level westerly winds from the eastern Pacific into the western Atlantic which, when combined with orographically-enhanced low-level southwesterly winds from Central America, promoted western Atlantic basin TCG. Yoo and Rohli (in preparation b) also suggested a potential influence of low-level wind enhancement in North America on western Atlantic TCG. When strong positive potential vorticity anomalies in the form of mid-latitude troughs occur with strong low-level convection over a vast region in mid-to-high latitude in the North America, occasionally an alley of low-level wind surge develops from the mid-latitude trough southward toward the western Atlantic, enhancing the large-scale low-level vortex of the developing storm (Yoo and Rohli, in preparation b). Sequential timing between the enhancement of this low-level wind surge alley and the intensification of Tropical Storm/Hurricane Cindy and Hurricane Dennis of 2005 was illustrated (Yoo and Rohli, in preparation b). Nevertheless, more case studies of TCG in the western Atlantic are warranted to characterize the role of large-scale TCG mechanism over the western Atlantic basin, where the large-scale geophysical features may culminate in favorable conditions to form a TC.

Hurricane Wilma (15-25 October 2005) was the most intense hurricane recorded in the Atlantic basin with the minimum central pressure of 882 hPa and an estimated peak sustained wind speed of 160 kt. Wilma caused twenty-three deaths and $20.6 billion of damages in the U.S. alone (Pasch et al., 2006). With the exception of cursory analysis in the TC report from the
National Hurricane Center (NHC), no study has been conducted to understand the relative importance of the atmospheric features discussed above in Wilma’s TCG.

To prepare for the potential future threats of major hurricanes such as Wilma, a review of the large-scale conditions from the early development stage of Wilma is helpful. The focus of the study is on the relative and collective roles of high-latitude PV anomaly, low-level wind surges transported by southern hemispheric subtropical high pressure systems, low-level westerly winds from eastern North Pacific, low-level northerly winds from mid/high latitude trough, and the orographic setting in Central America.

2. Data and Methods

The “best track” data by NHC is used as a guideline of the track and intensity changes of Hurricane Wilma in 2005. Large-scale sea surface temperature (SST) patterns are described using the NOAA optimum interpolation (OI) ¼ degree daily SST V2 data which include *in situ* SST measurements from ships and buoys, satellite observations from Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) sensor on NASA’s Aqua satellite and NOAA 17/NOAA 18 AVHRR, and National Centers for Environmental Prediction (NCEP) sea ice data (Reynolds et al., 2007).

The NCEP/National Center for Atmospheric Research (NCAR) Reanalysis (NNR) data (Kalnay et al., 1996) are used show the large-scale wind pattern during the development of Hurricane Wilma until it reached its peak maximum intensity over the Caribbean Sea by 1200 UTC 19 October. The period of decreased intensity after moving from Yucatan Peninsula to Florida will not be described in this study because the large-scale conditions that created the early TCG stage of Wilma are the main interest. The NNR dataset includes pressure level variables in 17 vertical layers on a global 2.5 by 2.5 degree grid. Hennon and Hobgood (2003)
noted that NNR data are superior to the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis dataset in the tropics.

Daily and long-term mean interpolated Outgoing Longwave Radiation (OLR) data provided by the NOAA/Oceanic and Atmospheric Research/Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD), Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/ (Liebmann and Smith, 1996) are used to produce the daily OLR anomalies that are used here to represent strong surface convection.

To run the Weather Research and Forecasting (WRF) model for Wilma, six-hourly NCEP FNL (final) operational global analysis data (1°x1°) and daily “real-time global” (RTG) SST data are used for three-dimensional input data and for SST update, respectively. The model run is set to update SST every six hours into the model integration. The NCEP Global Forecast System (GFS) final (FNL) gridded analysis datasets are used as an input data to run the WRF model. The FNL data for this study are obtained from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at NCAR. The original data are available from the RDA (http://dss.ucar.edu) in dataset number ds083.2. The RTG SST data are available from National Weather Service at ftp://ftp.polar.ncep.noaa.gov/pub/history/sst/. The WRF model is run globally to reproduce hourly hemispheric-to-meso-scale circulations, with SST updated daily during the model run (Table 5.1).
Table 5.1. Data sets used in Case Study 3.

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3. Hurricane Wilma in 2005 Overview

a) Large-scale Low-level Dynamics

After Tropical Storm Tammy (5-6 October 2005) diminished over Florida, a large-scale, low-
level wind surge (> 10 m s⁻¹) developed off the Atlantic coast of North America. This surge was
associated with a mid-latitude Rossby wave trough over the northern North Atlantic and a
subtropical high pressure to the east of North America. The mid-latitude trough seems to have
assisted the formation of the subtropical high to the east of North America and a frontal low in
the eastern North Atlantic, the latter of which later became Hurricane Vince (8-11 October 2005)
(Figure 5.1). Note that the shape of the subtropical high became deformed due to the frontal low
to the east of it. The abnormally strong frontal low also contributed to the weakened easterly
winds from western Africa. Meanwhile, vigorous southeasterly winds emanating from the south
Atlantic subtropical high produced strong low-level wind surges over a vast area northeast of
Brazil. Also, the synoptic-scale low-level vortex in the eastern North Pacific in early October
2005 seems to have been driven by persistent subtropical high pressure in the eastern South
Pacific near Chile. More detailed descriptions of the mechanism of the development of the low
level vortex in the eastern North Pacific is described in Yoo and Rohli (in preparation, a). The
synoptic-scale low-level vortex seems to be the main mechanism of the low-level westerly winds in the eastern North Pacific.

Although the intensities of the low-level wind surges changed slightly, the general setting of the large-scale low-level vortex distribution around Central America was maintained for an extended period of time. Specially, the western flank of the southeastern protrusion of the elongated North Atlantic subtropical anticyclone (Figure 5.1), which was northeast of the Caribbean Sea, became a zone for development of an unusually intense 850 hPa cyclonic vortex at the subsynoptic scale over 8 October (Figure 5.1). This vortex was produced as the easterly wind in the central tropical Atlantic weakened, allowing the cross-equatorial southeasterly wind east of the Caribbean Sea up to about 25°N, in the area of cyclonic vortex development (Figure 5.1 at 0000 UTC 8 October 2005). During 8-9 October, the abnormally large-scale low-level cyclone maintained its extended shape, from the southwestern Caribbean to the northeast. It is notable that the mid-latitude trough moved over the eastern North Atlantic as its associated Rossby wave progressed eastward by 0000 UTC 10 October. Accordingly, the 850 hPa wind surge around the western flank of the North Atlantic subtropical high, including over the east coast of the North America, weakened substantially. However, during 8-12 October, outflow to the north of the strengthening South Pacific subtropical high contributed to flow associated with a meso-scale quasi-anticyclonic rotation. The flow at the northern flank of this rotation allowed for strengthened westerlies (Figure 5.1, 5.2), leading to the development of an unusual subsynoptic-scale 850 hPa vortex in the next few days. The westerly winds were sufficiently strong to traverse the western Caribbean, where they converged with the southeasterly and easterly winds in the eastern Caribbean (Figure 5.2). This convergence reinforced the pre-existing subsynoptic-scale low-level cyclonic flow.
Figure 5.1. 850 hPa wind stream analysis of NNRP data and NOAA optimum interpolation (OI) ¼ degree daily SST V2 data superimposed by low-level wind surge. Areas of low-level wind surges exceeding 10 m s⁻¹ are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s⁻¹.
By 0000 UTC 13 October, the low-level cyclonic circulation became strong enough to generate a counterclockwise circulation with its own wind surge, even after the westerly winds weakened upon the disappearance of the eastern North Pacific low-level circulation. An 850 hPa wind surge developed from the low-level cyclonic flow poleward, east of the northeastern United States. Meanwhile, by 0000 UTC 14 October, meso-scale high and low pressure systems were developing over Texas and inland central Canada, respectively. This anticyclone grew quickly between the low over central Canada and the 850 hPa cyclonic circulation, the latter of which had broken down into two cyclonic circulations over the Caribbean and adjacent to the U.S. Atlantic coast – one on the northern and the other on the southern edge of the cyclonic zone (Figure 5.3). The enhancement of the northerly wind from the trough over central Canada near the meso-scale anticyclone over Texas accelerated the separation of the Caribbean/U.S. Atlantic coast zone of low pressure. The northern cyclonic circulation became an extratropical cyclone and the southern cyclone became more concentrated in the Caribbean Sea, near Jamaica by 14 October, becoming a tropical depression by 1800 UTC 15 October (Pasch et al., 2006). Pasch et al. (2006) suggested that tropical waves that were “traversing the Caribbean” might have been associated with this formation of the tropical depression. However, no tropical wave was “traversing” the Caribbean during that time. Instead, the 850 hPa streamline analysis shows clearly that the large-scale low-level wind was traversing the Caribbean from north to south even farther down to the equator (Figure 5.3).

By 1200 UTC 15 October, the high-latitude trough merged with the subtropical low that had been the northern part of the Caribbean/U.S. Atlantic coast cyclonic circulation, strengthening the subtropical low. The enhanced subtropical low played a role in prohibiting low-level easterly winds from the central tropical Atlantic from entering into the Caribbean Sea. Instead, these east-
Figure 5.2. As Figure 5.1 but for a different period of time.
Figure 5.3. As Figure 5.1 but for a different period of time.
Figure 5.4. As Figure 5.1 but for a different period of time.
erlies turned northerly to the east of the Caribbean Sea. This circulation allowed for the sustenance of the low-level circulation in the Caribbean Sea without significant interference by the zonally-propagating tropical waves (Figure 5.3-5.4).

Meanwhile, the tropical depression over the Caribbean Sea maintained its subsynoptic-scale vortex between the northerly winds associated with the trough in the northeastern U.S. and the southeasterly winds from the South Atlantic (Figure 5.3-5.4). But neither of the two 850 hPa circulations were strong enough to support a wind surge around the intensifying tropical depression. These two moderate drive trains caused the “weak and ill-defined steering” (Pasch et al., 2006) of the storm for the first few days of the storm that was to become Wilma. In this environment of only weak background and adjacent circulations, the depression slowly strengthened over 16 October and became a tropical storm at 0600 UTC 17 October.

Over 17-18 October, as the mid-latitude trough over the northeastern U.S. progressed eastward, the North Atlantic subtropical high strengthened and began to produce more vigorous low-level easterly winds in the central tropical Atlantic toward the Caribbean Sea. At the same time, the mid-latitude trough continued to support 850 hPa northerly winds from the Great Lakes region to the west of Wilma (through Central America), thereby enhancing cyclonic vorticity in Wilma (Figure 5.5). During that time, Wilma drifted toward the west-northwest and strengthened into a hurricane at 1200 UTC 18 October. An explosive deepening occurred during the night and Wilma’s maximum sustained wind speed had increased to near 150 kt (category 5 on the Saffir-Simpson Hurricane Scale) by 0600 UTC 19 October (Pasch et al., 2006). It should be noted that this unprecedented rapid intensification of Hurricane Wilma took place under the anomalously meridionally developed low-level circulations in the synoptic-scale (Figure 5.6). As Hurricane
Figure 5.5. As Figure 5.1 but for a different period of time.
Figure 5.6. As Figure 5.1 but for a different period of time.
Wilma was lingering in the northern Caribbean, an 850 hPa southwesterly wind surge alley developed over the southern Great Plains beginning around 0600 UTC 19 October (Yoo and Rohli, in preparation, b). By 1200 UTC 19 October, the peak sustained wind speed of 160 kt was recorded for Wilma with the estimated minimum central pressure of 882 hPa - the lowest pressure recorded for a hurricane in the Atlantic basin (Pasch et al., 2006).

b) Large-scale Sea Surface Temperature Conditions

During the lifespan of Wilma, SST in the entire western Atlantic basin and central tropical Atlantic exceeded the 26°C climatological threshold for TC development (e.g. Gray, 1968), with western Atlantic SST peaking at over 30°C (Figure 5.7). The general SST condition over the western Atlantic was warmer than average while the southern Caribbean and central Atlantic had even stronger positive anomalies during 1-21 October 2005 (Figure 5.8). During the same period, however, SST was below average over the eastern North Pacific.

SST changes over 3 and 6 days are depicted in Figures 5.9 and 5.10, respectively. Generally, SST over the Atlantic remained constant or increased slightly. Interestingly, 6-day SST change maps clearly show significant SST decreases in the Atlantic during October. SST decrease during 1-7 October over a broad area in the northern Atlantic seems to be related to the passage of a mid-latitude trough that was associated with Tropical Storm Tammy (5-6 October) (See Figure 5.1). The decreasing SST in the Caribbean during 7-13 October represents the evaporation from the ocean while the tropical depression (Wilma) was developing. The SST change map for 13-19 October 2005 suggests sea surface energy consumption by Hurricane Wilma during its early explosive intensification in the northwestern Caribbean Sea. Finally, the SST decrease in the central tropical Atlantic provides evidence of the vigorous low-level southeasterly and easterly wind surges during 19-25 October 2005 (Figure 5.6).
Figure 5.7. SST over the tropical and western Atlantic every four days during 1-21 October 2005. The thick contour lines are drawn at a 3 °C interval and SSTs exceeding 26°C are contoured with dark shades at a 1 °C interval.
Figure 5.8. SST anomalies over the tropical and western Atlantic every four days during 1-21 October 2005. Contour lines are drawn at a 1°C interval. Positive anomalies are contoured with dark shades at a 1°C interval and negative anomalies are drawn with dashed line contours.
Figure 5.9. SST change over 3-day intervals over the tropical and western Atlantic during 1-25 October 2005. Contour lines are drawn at a 1 C° interval. SST increases are contoured with dark shades at a 1 C° interval and SST decreases are drawn with dashed line contours.
c) Potential Vorticity in the Upper-Level Atmosphere and Outgoing Longwave Radiation

In general, mid-latitude troughs are associated with lower-level instability downwind of the trough as they provide energy and momentum from the high latitudes and incorporate moisture from the lower latitude (Yoo and Rohli, in preparation, b). An upper-tropospheric trough in the Rossby waves has positive PV by nature, as shown in Figure 5.11. The unit of the potential vorticity (PV) (PVU) is $10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$. On the right side of the panel in Figure 5.11, the locations of negative OLR anomalies represent the regions where active convection is occurring.

In the mid-latitudes, positive PV anomaly regions correspond to locations of 850 hPa wind surges, and those wind surges seem to be related to high convection in the OLR anomaly map. However, those relationships do not apply to the lower-latitude region. Generally, PV is significantly weaker in the lower latitudes than in the mid-latitude. Nevertheless, strong convection can occur in the lower-latitude even with mild wind speeds mainly because SST
conditions tend to be much more favorable in the lower latitudes than in the mid-latitudes (Figure 5.7 and 5.11).

During the TCG period of Hurricane Wilma, the presence of Hurricane Vince (8-11 October 2005) and his interplay with subsequent large-scale vortices in the eastern North Atlantic caused a rather unusual PV distribution over North America. By 0600 UTC 14 October, the zone of positive PV was elongated southward (Figure 5.11), with a sharp north-to-south and south-to-north circulation pattern following over the continent in the aftermath of Wilma’s TCG.

During Wilma’s explosive deepening (from 1200 UTC 18 October to 1200 UTC 19 October), a strong positive PV was located over the northeastern coast of the United States. This PV was associated with the troughs in the northern North Pacific and central Canada (Figure 5.11, 0600 UTC 18 October). It seems that the positive PV over the northeastern coast of the U.S may have also assisted in the spin-up of the regional anticyclone over Texas and the subtropical high in the North Atlantic. Both of the two anticyclones seem to have contributed to the intensification of Wilma at the 850 hPa level by advecting angular momentum to the outer radii of Wilma. The mid-latitude troughs were separated from each other and the regional anticyclone over Texas became suppressed as Wilma deepened during 19 October. Subsequently, Wilma’s intensity decreased on 20 October by 30 kt (still leaving her as a Category 4 hurricane) from 160 kt at 1200 UTC 19 October. However, positive PV over the northeastern coast of the U.S. remained strong and the easterly winds from the central tropical Atlantic strengthened. These events suggest that large-scale circulation pattern in the immediate TC environment plays an important role in TC intensity change, a finding consistent with that of Miller (1958). The multi-directional sources of angular momentum advection as described here likely provided for more efficient intensification than if angular momentum inflow had been from a sole source, such as regional low-level easterlies.
Meanwhile, the sequential images of negative OLR anomaly beginning at 0600 UTC 11 October (Figure 5.11) clearly show the cyclonic circulation development over the Caribbean and adjacent western North Atlantic. This depression which later became Wilma had been attributed to the westerly wind surge over the eastern North Pacific. The negative OLR anomaly maps after the TCG of Wilma show that Hurricane Wilma’s explosive deepening (from 1200 UTC 18 October to 1200 UTC 19 October) was favored by the persistent low-level inflow from the large convective region in the Caribbean Sea and the central tropical Atlantic, which is consistent with SST change over the period (Figure 5.9 - 5.10).

4. WRF Model Simulation
A WRF model run was executed to examine the process of TCG with improved spatial and temporal resolution, using Hurricane Wilma in 2005 as a case study with a global model domain setting. The global WRF model domain was set with (x, y) dimensions of 721 × 361 (d01) (Figure 5.12). The global domain has a grid size of 55.58874 km in the x and y directions. The model microphysical schemes are configured following the NCAR Advanced Hurricane WRF (AHW) microphysics guidelines, including i) the Lin et al. (1983) cloud microphysics scheme; ii) the Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation (Mlawer et al., 1997); iii) the Dudhia (1989) scheme for shortwave radiation; iv) the Yonsei University planetary boundary layer (PBL) parameterization; v) the Monin-Obukhov scheme for the surface layer option; vi) the thermal diffusion scheme for the land surface physics; and vii) Kain-Fritsch (new Eta) scheme for the cumulus parameterization (Gilliland and Rowe, 2007) (Table 5.2). The 38 sigma (σ) level set of Kieu and Zhang (2008) was applied. The model “top” is defined at 50 hPa. The model run was set to update SST every six hours into the model integration. The daily RTG SST data were interpolated sequentially to produce 6-hourly input data for the WRF run.
Figure 5.11. Evolution of the distribution of 200 hPa potential vorticity (PVU, shaded) (left) and negative OLR anomalies (W m\(^{-2}\), shaded) (right) with 850 hPa streamline analysis superimposed on the low-level wind surge. The contour interval for OLR anomalies is 30 W m\(^{-2}\). Areas of 850 hPa wind surges exceeding 10 m s\(^{-1}\) are enclosed by dots within the thick solid contour lines, for which the interval is 15 m s\(^{-1}\); 11-22 October 2005.
Figure 5.11. Continued.
Figure 5.11. Continued.
Table 5.2. Physics options implemented in the WRF model simulation.

<table>
<thead>
<tr>
<th>Physics options</th>
<th>Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>The Lin et al. (1983) cloud microphysics scheme</td>
</tr>
<tr>
<td>Longwave radiation</td>
<td>The Rapid Radiative Transfer Model (RRTM) scheme</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>The Dudhia (1989) scheme</td>
</tr>
<tr>
<td>Boundary layer option</td>
<td>The Yonsei University planetary boundary layer (PBL) parameterization</td>
</tr>
<tr>
<td>Surface layer option</td>
<td>The Monin-Obukhov scheme</td>
</tr>
<tr>
<td>Land surface physics</td>
<td>The thermal diffusion scheme</td>
</tr>
<tr>
<td>Cumulus parameterization</td>
<td>Kain-Fritsch (new Eta) scheme (applied only for the domains larger than 10 km resolution)</td>
</tr>
</tbody>
</table>

Figure 5.12. The model domain of global WRF for Hurricane Wilma in 2005. NHC best tracks were plotted with its major intensity changes annotated (See Figure 1.1 for more track information).

In the global WRF model simulation, two different runtimes were executed. The first simulation runs from 0000 UTC 7 October to 0000 UTC 21 October, to include the anomalous circulation that Hurricane Vince introduced in the North Atlantic about one week before the TCG of Wilma – a duration of 336 hours. The second simulation runs from 0000 UTC 14 October to 0000 UTC 21 October, which only includes the pregenesis condition, TCG, and the
development of Wilma – a duration of 168 hours. Both simulations end on 0000 UTC 21 October though Wilma continued to maintain hurricane intensity until 1800 UTC 25 October. The latter half of the first model simulation result will be compared to the result of the second run to evaluate the accuracy of the global WRF model.

5. WRF Model Analysis

Compared to Figure 5.1 and 5.2, the global WRF reproduced large-scale atmospheric circulations at 1500 m (about 850 hPa) very closely and effectively (Figure 5.13). Wind conditions at the time of model integration are presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to blue (0 – 46 m s\(^{-1}\)). The yellow to purple scale in the background represents the water vapor in the range of 12 - 20 g kg\(^{-1}\). The deformation of the low-level circulation by Hurricane Vince (8 – 11 October) and the subsequent development of the anomalous low-level cyclone over and northeast of the Caribbean by the westerly winds from eastern North Pacific were simulated very realistically.

However, the “realistic” simulation of the global WRF model did contain errors, as shown in Figure 5.14. The error growth seven days after the model initialization made the large-scale circulations shift enough to prevent the model from replicating the TCG of Wilma and its subsequent development into a hurricane over the western North Atlantic (not shown). From the Figure 5.14, it seems that the major error comes from the high latitudes and mid-latitude systems that are directly affected by the high-latitude circulations. In fact, during the prolonged simulation, the major failure occurred in reproducing the interactions between the mid-latitude trough over the northeastern U.S. and the subtropical low to the east of the United States. As a result, the “different” intensity and location of the mid-latitude trough to the northeast of the disturbance that was in the Caribbean changed the condition of the subtropical high in the North
Atlantic during the actual period of Wilma, producing vigorous easterly winds over Central America (Figure 5.15). This zonally-enhanced low-level wind condition is opposite to the meridionally-enhanced, low-level condition in the actual case of Wilma. Nevertheless, even the failed simulation suggests the important fact that the \textit{in situ} condition of the large-scale, low-level circulations heavily affects TCG.

![Figure 5.13. Global WRF model simulation output. Sample dates and times are comparable to those in Figure 5.1 and 5.2. Wind conditions at 1500 m (about 850 hPa) at the time of model integration are presented with arrows. The color of the wind arrows represents wind speed: wind speed increases as the color changes from red to blue (0 – 46 m s\(^{-1}\)). The yellow to purple in the background represents the water vapor in the range of 12 - 20 g kg\(^{-1}\).]
Figure 5.13. Continued.
Figure 5.13. Continued.
By contrast, the second simulation that was initialized at 0000 UTC 14 October successfully simulated the TCG of Wilma and its subsequent development (Figure 5.16). The WRF global model could reproduce every major large-scale vortex and circulation at 850 hPa level not only over the North Atlantic but also over the neighboring basins, including the eastern Pacific, South Atlantic, and subpolar regions. But the forecasted track of Wilma shifted to the east from the actual best track when Wilma was in its hurricane stage. This error seems to be attributed to the use of a relatively large grid size for the model simulation (55.58874 km) to represent the meso-scale features accurately, while the inner-core dynamics of the storm actually played a more important role in steering its path and determining its intensity.

The successful forecast of the merger of the subtropical cyclone with the mid-latitude trough off the east coast of the U.S. around 16 October seems to be the key point that led the subsequent successful forecasts in the unique low-level, large-scale circulation development in the case of Wilma (see Figure 5.3 - 5.6 and 5.16 in this chapter). This means that the role of mid-latitude systems in TC activity is not negligible. However, current TCG forecasting efforts largely focus only on tropical atmospheric conditions. The comparison of the unsuccessful and the successful forecasts of the TCG and development of Wilma suggests that every large-scale vortex and circulation component at least in the immediately-neighboring storm development area is important for TCG forecasting.

Although the calculation errors in the global WRF model simulation grew significantly after seven days of model integration, it seems that the global WRF can be used for the purpose of operational short-range TCG forecasting. This result is encouraging, considering the fact that the global WRF model that was initialized 42 hours before the official TCG simulated Wilma’s TCG and subsequent development very accurately in one continuous simulation for the seven-day period. It should be also noted that the seven-day global WRF model simulation took only less
than 6 hours in a Linux cluster computer with 96 cores at Louisiana State University (LSU) High
Performance Computing (HPC).

Figure 5.14. Comparison of the large-scale low-level circulations between the global WRF
model result after a seven-day simulation (a) and the model initialization condition with FNL and
RTG SST data sets at 0000 UTC 14 October.
Figure 5.15. A failed forecast of Wilma’s TCG.
Figure 5.16. A successful forecast of Wilma’s TCG.
Figure 5.16. Continued.
6. Discussion and Conclusion

In this study, large-scale atmospheric and oceanic conditions of the western Atlantic basin were analyzed to understand the unique TCG and intensification mechanism of Hurricane Wilma in 2005, using NCEP/NCAR Reanalysis data, NOAA optimum interpolation (OI) ¼ degree daily SST V2 data, NOAA/OAR/ESRL PSD Interpolated OLR data, and global WRF model simulation.

An anomalous development of the 850 hPa circulation pattern in the North Atlantic was triggered by Hurricane Vince (8-11 October 2005). Circulation around the southeastern fringe of the North Atlantic subtropical anticyclone had been interrupted by the presence of Vince, causing a perturbation in the downstream flow around the entire southern edge of the north Atlantic subtropical high. On the southwestern flank of the subtropical high, the perturbation contributed to development of a large-scale 850 hPa vortex that would eventually allow for Wilma’s TCG in the eastern Caribbean Sea. Due to the change in the low-level circulation by the deformed subtropical anticyclone, weakened low-level easterly winds allowed southeasterly winds from the southern hemisphere and westerly winds from eastern North Pacific to become relatively more important, generating an anomalously large-scale low-level cyclone over the western Atlantic about a week before the TCG of Wilma.

The anomalously large low-level cyclone over the western Atlantic matured over the warm ocean before it was separated into two cyclones in a north-south alignment. The separation was caused by the advance of northerly winds from a mid-latitude trough over central Canada one day before TCG. By 1200 UTC 15 October, the high-latitude trough merged with the northern cyclone, resulting in a strengthened northern subtropical low. The enhanced subtropical low eventually played a role in sustaining the low-level circulation in the Caribbean Sea by preventing significant interference from the zonally-propagating tropical waves (Figure 5.3-5.4).
The southern cyclone became more concentrated in the Caribbean Sea, near Jamaica by 14 October, becoming a tropical depression by 1800 UTC 15 October.

The unusual but persistent circulation conditions allowed the tropical depression over the Caribbean Sea to strengthen slowly between the northerly winds associated with the trough in the northeastern U.S. and the southeasterly winds from the South Atlantic (Figure 5.3-5.4). Wilma became a tropical storm at 0600 UTC 17 October. Over 17-18 October, as the North Atlantic subtropical high strengthened to produce more vigorous low-level easterly winds in the central tropical Atlantic toward the Caribbean Sea (Figure 5.5), Wilma drifted toward the west-northwest and strengthened into a hurricane at 1200 UTC 18 October.

The unprecedented rapid intensification of Hurricane Wilma during the night took place over anomalously warm SST conditions when Wilma was trapped between the northerly winds from the mid-latitude trough and synoptic-scale southeasterly winds. During Wilma’s explosive deepening, the cumulative effects of three mid-latitude troughs created strong positive PV from the northern North Pacific through central Canada over to the northeastern coast of the United States. The positive PV over the northeastern coast of the U.S. seems to have influenced the regional surface anticyclone over Texas and the North Atlantic subtropical high. The shear from both anticyclones caused Wilma to intensify between them by advecting angular momentum to the outer radii of Wilma.

The global WRF reproduced large-scale atmospheric circulations at 1500 m (about 850 hPa) very closely and effectively including the deformation of the low-level circulation by Hurricane Vince (8 – 11 October) and the subsequent development of the anomalous low-level cyclone over and northeast of the Caribbean. However, the error growth after seven days from the model initialization changed the large-scale circulations, resulting in a failed forecast of Wilma’s TCG and subsequent development into a hurricane over the western North Atlantic. It seems that the
major error comes from misrepresenting the interactions between mid-/high-latitude systems and tropical circulations. Nevertheless, even the failed simulation stresses the important fact that the in situ condition of the large-scale, low-level circulations heavily affects TCG.

In contrast, the second simulation that was initialized at 0000 UTC 14 October successfully simulated the TCG of Wilma and its subsequent development (Figure 5.16). The WRF global model reproduced every major large-scale vortex and circulation at the 850 hPa level, not only over the North Atlantic but also at least over the neighboring eastern Pacific, South Atlantic, and subpolar ocean basins. With the successful simulation of the merger of the subtropical cyclone with the mid-latitude trough off the east coast of the U.S. around 16 October, the subsequent forecast of the global WRF model was maintained successfully, reproducing the unique low-level, large-scale circulation development in the case of Wilma (see Figure 5.3-5.6 and 5.16). The result of the global WRF model suggests that the role of mid-latitude systems in TC activity is more important than previously considered, and that every large-scale vortex and circulation component at least in the immediately-neighboring region of the storm developing area is important for TCG forecasting. This study has shown that the global WRF has a potential to be used for operational short-range TCG forecasting.

7. References


CHAPTER 6. SUMMARY

A series of studies in this dissertation examined influences of large-scale atmospheric circulation on TCG and intensity change mechanisms for selected storms in the 2005 Atlantic hurricane season. The topic was approached only with the dynamical analyses of the atmospheric circulation, excluding the influence of teleconnections such as Madden-Julian Oscillation (MJO), El Niño / Southern Oscillation (ENSO), and North Atlantic Oscillation (NAO). Various observed and derived data sets were used, including National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (NNR) data, National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) ¼ degree daily sea surface temperature (SST) Version 2 data, and NOAA / Oceanic and Atmospheric Research / Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD) Interpolated Outgoing Longwave Radiation (OLR) data. Six-hourly NCEP FNL (final) operational global analysis data and daily “real-time global” (RTG) SST data were used as input data for Weather Research and Forecasting (WRF) model (V.3.2.1) to reproduce the atmospheric conditions at the times of tropical cyclogenesis (TCG) and intensity changes of investigated tropical cyclones (TCs) that formed in the western Atlantic basin or Gulf of Mexico/Caribbean basin: Tropical Storm Arlene and Hurricanes Cindy, Dennis, and Wilma in 2005. GOES-12 satellite water vapor imagery was used to validate the NNR data and the WRF model simulations. By contrast, TCG of the well-studied and more notorious storms of 2005 (Katrina and Rita) was excluded in this study because easterly waves from Africa are well-known to be a harbinger of major TCs for such storms that develop in the eastern North Atlantic basin.

Key findings in the case study of Tropical Storm Arlene (8 – 13 June 2005) include the following:
1) complicated interactions among low-level vortices in the tropical eastern Pacific region generated the “temporarily consistent” westerlies from the warm eastern Pacific into the Caribbean Sea for about two weeks before the Arlene developed;

2) westerlies from the eastern Pacific and the southeasterlies from the southern hemisphere created a confluence region in the Caribbean, which generated strong positive low-level meso-scale vorticity over the warm sea surface, leading to a tropical depression at 1800 UTC 8 June;

3) a funneling of westerlies between mountain passes in Central America resulted in increasing westerly wind speed;

4) the southeast trade winds from the southern hemisphere played a major role in strengthening the tropical depression into Tropical Storm Arlene, while an 850 hPa anticyclone east of the U.S. was engaging with the storm from the east and the northeast;

5) the timing of maximum intensification and the sudden weakening of Arlene was linked to the strong moisture advection provided by the westerlies/southeasterlies and the isolation of the storm from the intense moisture supply from the low latitudes after it advanced far northward into the Gulf of Mexico, respectively.

To understand the TCG and intensification mechanisms of Hurricanes Cindy (3 – 7 July) and Dennis (4 – 13 July), large-scale atmospheric and oceanic conditions of the western Atlantic basin were analyzed. Major conclusions are:

1) during the period of strong positive SST over the western Atlantic anomaly, positive potential vorticity (PV) anomalies in the 250 hPa mid-latitude trough affected the large-scale low-level circulation southward to the tropics, possibly influencing the development of
vigorous low-level meso-scale convective vortices (MCVs) with the topographic effects over the Caribbean Sea;

2) southeasterly winds from the South Atlantic also played a major role in amplifying 850 hPa easterly winds over the Caribbean Sea, creating an anomalously large planetary-scale wind surge over the tropical Atlantic;

3) the sequence of development and intensity changes of the storms were well-responsive to the development of the low-level wind surges either by the mid-latitude trough poleward of the storm or by the southeasterly/easterly winds equatorward of the storm, which was verified by the location of OLR anomalies and the WRF model simulations. It seems that the planetary-scale, low-level circulations from the Southern Atlantic to the northern hemisphere’s mid-latitudes play a significant role in creating the low-level conditions necessary for the meso-scale internal processes of the storm core to achieve TCG and its maximum intensity over the western Atlantic basin.

4) it seems that global numerical model simulation outperforms regional model simulation in representing the large-scale circulation patterns that are highly critical in TCG and tropical cyclone (TC) forecasts.

In the efforts to understand the unique TCG and intensification mechanism of Hurricane Wilma (15–25 October) in 2005, the following results were found:

1) Hurricane Vince (8-11 October 2005) created a unique 850 hPa circulation pattern over the North Atlantic, causing a large-scale 850 hPa cyclonic circulation on the southwestern flank of the subtropical high in the basin which eventually facilitated Wilma’s TCG;

2) weakened low-level easterly winds due to the anomalous low-level circulation in the North Atlantic introduced balanced stronger counter-blows of southeasterly winds from the southern
hemisphere and westerly winds from eastern North Pacific into the western North Atlantic, generating an anomalously large-scale, low-level cyclone about a week before the TCG of Wilma;

3) the advance of northerly winds from a mid-latitude trough over central Canada one day before the TCG of Wilma and the anomalously warm SST matured the tropical disturbance in the Caribbean Sea. The dynamical interactions of the mid-latitude trough with a subtropical low maintained the northerly winds, which sustained the low-level circulation in the Caribbean Sea by preventing significant interference from the zonally-propagating tropical waves. The unusual but persistent circulation conditions of the northerly winds and the southeasterly winds from the South Atlantic intensified Wilma to tropical storm status by 0600 UTC 17 October;

4) the unprecedented rapid intensification of Wilma seems to have been triggered by the anomalously warm SST conditions and the unique large-scale low-level circulation pattern that trapped Wilma between the northerly winds from the mid-latitude trough and synoptic-scale southeasterly winds as well as by the angular momentum advection from neighboring regional surface anticyclones over Texas and the North Atlantic subtropical high.

5) the results of the global WRF model simulations suggest that the role of mid-latitude systems in TC activity is more important than was previously believed and that every in situ large-scale vortex and circulation component at least in the immediately-neighboring storm development area is important for TCG.

The summary of the results clearly supports that the confluence of multiple planetary-scale atmospheric circulations generate a meso-scale vortex over the western North Atlantic basin, leading to TCG. This result satisfies the condition of the hypothesis of this study. While the
monsoon trough is the breeding region of most TCs in the western North Pacific basin, little evidence exists in previous literature for a monsoon trough region in the western Atlantic. However, this study has shown that an analogous monsoon trough region was created temporarily over Central America when the westerly wind from the eastern North Pacific, southeasterly wind emanating from the subtropical high in the South Atlantic, and easterly winds from the central tropical Atlantic created a confluence region over the Caribbean Sea at a time when the SST in the region became anomalously warm. This is consistent with the climatological explanations of the anomalously active Atlantic hurricane season in 2005 (Bell et al., 2006). Interestingly, low-level wind surges in this study have features similar to low-level jets (LLJs) (Hoecker, 1963; Bonner, 1968; Stensrud, 1996). In particular, the development mechanism, role in regional climate, and interaction with extratropical circulation systems of the LLJ in the Caribbean Sea known as the Intra-Americas Sea low-level jet (IALLJ) is uncertain (Amador, 2008). The planetary-scale perspectives of this study with wind surges by southeasterly/easterly winds over the Caribbean Sea may contribute to the understanding of the local LLJs.

1. References


CHAPTER 7. CONCLUSION

This study has clearly shown the tropical cyclogenesis (TCG) mechanism in the western North Atlantic for several 2005 storms, with emphasis on the large-scale, low-level atmospheric circulations. Three case studies suggest that the planetary-scale atmosphere circulations must be monitored for improvement of TCG forecasting, and interactions of every component of *in situ* low-level circulations have been found to determine the location and time of TCG. The scale of atmospheric circulations that affect the TCG in the western North Atlantic is large to include the Northeast Pacific, Southeast Pacific, and South Atlantic as well as North Atlantic. In particular, the interactions between mid-latitude troughs and the tropical disturbance with the consequent development of a low-level jet-related wind surge alley from the southern edge of the mid-latitude troughs in the wake of southeasterly wind surges from the South Atlantic should be watched more closely for potential TCG or for sudden intensification of a incumbent tropical cyclone. As a result of dynamical interactions between low-level vortices in the Pacific, occasional development of westerly wind surges from the eastern North Pacific also increases the possibility of TCG over the western North Atlantic by creating a confluence area over the warm Caribbean. To improve TCG predictability, these macro-scale points of view should complement the current TCG forecasting strategies which focus mainly on meso-scale atmospheric features. The fact that the low-level circulations from the southern hemisphere played a critical role in TCG implies that cross-hemispheric planetary circulation may be more active and important in TCG than previously thought. This result may also suggest that the relationship between TCG and global-scale circulation, including polar activity, is more direct than previously believed.

Weather Research and Forecast (WRF) model simulations showed that error propagation from the boundary condition in the regional domain run heavily affects the development of low-level
atmospheric circulations within a few days of model integration, decreasing the predictability significantly. However, the global WRF model showed a respectable performance in the reproduction of the low-level atmospheric circulations over an extended period of model run of about seven days. However, the reproduction of areas of active atmospheric motion such as mid-latitude troughs suffers more degradation in the latter period of model simulation.

For the purpose of practical application in tropical cyclone forecasting, weather authorities should consider planetary-scale, low-level circulations and vortex developments in the East Pacific for improved preparedness for Western Atlantic tropical cyclones. Also, close monitoring the latitudinal location and strength of the PV anomalies of the mid-latitude trough, the condition of the southeasterly wind surge from the South Atlantic, and the easterlies should all be considered before promulgating TC forecasts. Further modeling study with observation data assimilation is needed to clarify the pole-to-tropical interaction and its impact on TCG. These results are useful to environmental planners, policymakers, and emergency responders as they seek additional clues for extending the time available for evacuation in heavily-populated areas.
VITA

Jinwoong Yoo was born on 10 April 1975, in Busan, Korea. He earned his Bachelor of Arts degree in Geography from Seoul National University in 1999. Afterwards, he served in the Republic of Korea Marine Corps as a platoon leader for two years and finished the service as a lieutenant. He enrolled in the Master of Arts in Geography program at the Seoul National University in 2001. He received a Master of Arts in Geography in 2003. His thesis title was, “Estimation of Evapotranspiration with SEBAL Model in the Geumgang Upper Basin, Korea” (Seoul: Seoul National University Library, Korea). His thesis advisor was Dr. Keun-Bae Yu. In 2004, he enrolled in the Department of Geography and Anthropology at Louisiana State University for his doctoral program. Inspired by Hurricane Katrina in 2005, he carried out a broad study of tropical cyclones from genesis to maximum intensity, under the supervision of Dr. Robert Rohli. Finally, he used various scientific methods including the Weather Research and Forecasting (WRF) model to investigate the large-scale characteristics of tropical cyclogenesis and hurricane intensity change in the western North Atlantic basin. He will be awarded the degree of Doctor of Philosophy at the May 2011 commencement.