THE INFLUENCE OF MOISTURE, VERTICAL WIND SHEAR AND STORM MOTION ON THE RAINFALL DISTRIBUTION PATTERN OF TROPICAL CYCLONES IN THE SOUTHERN GULF COASTAL STATES

By
Sanghoon Kim

A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA
2017
To my family and all who supported me
I would like to say thank you for all who support me to finish the thesis. First, I appreciate my advisor, Dr. Corene Matyas, for the guidance of my hurricane studies during my master's program. She tried not to give the answers immediately for questions, but encouraged me to find the right direction to pursue research about hurricanes. She has reviewed this thesis intensely to be publishable and is supported with a grant from the National Science Foundation (BCS-1053864). Also, I would like to thank Dr. Mossa and Dr. Binford for being members of my committee. I also thank the hurricane group members, and especially Yao Zhou. They gave me helpful feedback for this research in terms of datasets and methods.

Finally, I would like to dedicate all my appreciation to my family. My wife, my son, my parents, and my brother gave me endless support to study in the United States.
# TABLE OF CONTENTS

**ACKNOWLEDGMENTS** ........................................................................................................... 4

**LIST OF TABLES** .................................................................................................................. 6

**LIST OF FIGURES** .................................................................................................................. 7

**ABSTRACT** ............................................................................................................................. 8

**CHAPTER**

1  **INTRODUCTION** .................................................................................................................. 10

2  **THE INFLUENCE OF MOISTURE, VERTICAL WIND SHEAR AND STORM MOTION ON THE RAINFALL DISTRIBUTION PATTERN OF TROPICAL CYCLONE IN THE SOUTHERN GULF COASTAL STATES** .................................................................................................................. 21

## 1 INTRODUCTION

- Introduction .............................................................................................................................. 21
- Literature Review .................................................................................................................... 21
  - Vertical Wind Shear and Storm Motion ................................................................................. 21
  - Tropical Cyclone Intensity ..................................................................................................... 22
  - Topography .......................................................................................................................... 22
  - ET process ............................................................................................................................ 23
  - Moisture ............................................................................................................................... 24
  - Tropical Cyclone Rainfall and Total Precipitable Water ....................................................... 24
- Research Objectives ................................................................................................................. 26
- Data and Methods .................................................................................................................... 27
  - Tropical Cyclone Datasets .................................................................................................... 27
  - Methods ............................................................................................................................... 29
- The Results ............................................................................................................................... 34
  - TPW Conditions .................................................................................................................. 34
  - Vertical Wind Shear and Storm Motion ................................................................................. 37
  - Rainfall Patterns .................................................................................................................. 37
  - Rainfall Patterns by TPW, Vertical Wind Shear and Storm Motion ....................................... 38
- Discussion and Limitations ....................................................................................................... 43

3  **CONCLUSION** ..................................................................................................................... 63

**LIST OF REFERENCES** .......................................................................................................... 67

**BIOGRAPHICAL SKETCH** .................................................................................................... 75
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>The 12 selected storms (Western Group) that made landfall over from 1998 to 2015</td>
<td>46</td>
</tr>
<tr>
<td>2-2</td>
<td>The 17 selected storms (Central Group) that made landfall over Louisiana, Mississippi, Alabama, and the western Florida from 1998 to 2015</td>
<td>46</td>
</tr>
<tr>
<td>2-3</td>
<td>The 14 selected storms (Eastern Group) that made landfall over Florida Peninsula from 1998 to 2015</td>
<td>47</td>
</tr>
<tr>
<td>2-4</td>
<td>The Mann-Whitney U Test results (p-values) of the averaged total TPW during 24 hours</td>
<td>48</td>
</tr>
<tr>
<td>2-5</td>
<td>The Mann-Whitney U Test results (p-values) of the averaged total TPW on the left side (Cells 1, 4, 7) of storm motion during 24 hours</td>
<td>48</td>
</tr>
<tr>
<td>2-6</td>
<td>The Mann-Whitney U Test results (p-values) of the averaged total TPW on the right side (Cells 3, 6, 9) of storm motion during 24 hours</td>
<td>49</td>
</tr>
<tr>
<td>2-7</td>
<td>The Mann-Whitney U Test results (p-values) of the averaged total TPW on the left side (Cells 1, 4, 7) versus on the right side (Cells 3, 6, 9) of the storm during 24 hours</td>
<td>49</td>
</tr>
<tr>
<td>2-8</td>
<td>The Mann-Whitney U Test results (p-values) of the angle difference between vertical wind shear and storm motion between two groups</td>
<td>50</td>
</tr>
<tr>
<td>2-9</td>
<td>The Mann-Whitney U Test results (p-values) of the storm total volumetric rain over the entire outlined area between the left and the right side of storm motion at t00 by groups</td>
<td>50</td>
</tr>
<tr>
<td>2-10</td>
<td>The percentage of storms’ rainfall patterns that can be explained by TPW or vertical wind shear and storm motion</td>
<td>50</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>The study region within the Gulf of Mexico and the Gulf coastal states in the U.S.</td>
</tr>
<tr>
<td>2-1</td>
<td>Three regional groups with selected storm tracks every 3 hours from 24 hours prior to landfall to the time closest to landfall</td>
</tr>
<tr>
<td>2-2</td>
<td>The amount of TPW at 00 UTC 29 August 2005 during the landfall of Hurricane Katrina</td>
</tr>
<tr>
<td>2-3</td>
<td>Regions where the rain rate exceeds of 5 mm hr$^{-1}$ were selected for analysis</td>
</tr>
<tr>
<td>2-4</td>
<td>The symmetry of TC rainfall distribution</td>
</tr>
<tr>
<td>2-5</td>
<td>The boxplots for the averaged total TPW in the grid boxes surrounding storms by regional groups during 24 hours</td>
</tr>
<tr>
<td>2-6</td>
<td>The boxplots for the averaged total TPW on the left side (Cells 1, 4, 7) of storm motion by regional groups during 24 hours</td>
</tr>
<tr>
<td>2-7</td>
<td>The boxplots for the averaged total TPW on the right side (Cells 3, 6, 9) of storm motion by regional groups during 24 hours</td>
</tr>
<tr>
<td>2-8</td>
<td>The 40mm line of TPW boundary at t00</td>
</tr>
<tr>
<td>2-9</td>
<td>The boxplots for the averaged shortest distance between the storm centers and TPW contour line of 40 mm by regional groups during 24 hours</td>
</tr>
<tr>
<td>2-10</td>
<td>The boxplots for the distance to TPW contour line of 40mm at t00 by the rainfall distribution pattern</td>
</tr>
<tr>
<td>2-11</td>
<td>The averaged storm motion vector and the averaged vertical wind shear vector in quadrants by regional groups</td>
</tr>
<tr>
<td>2-12</td>
<td>The boxplots for the total volumetric rainfall over the entire outlined area at t00 by groups</td>
</tr>
<tr>
<td>2-13</td>
<td>The boxplots for the volumetric rainfall over the entire outlined area between the left and the right side of storm motion at t00 by groups</td>
</tr>
<tr>
<td>2-14</td>
<td>The number of cases exhibiting each rainfall distribution patterns by group</td>
</tr>
</tbody>
</table>
Tropical cyclones (TCs) cause a lot of damage to society when they make landfall due to heavy rainfall and flash flooding. Many scientists have studied TC rainfall patterns to improve the forecasting of TC rainfall in order to reduce the impacts of flooding. However, there is still a need to improve the prediction of the spatial distribution of rainfall so that forecasts can be more accurate. A large supply of moisture is required to sustain TC rainfall production. When the relatively dry air that exists over the land surface intrudes into a TC, less rainfall should be produced on that side of the storm due to increased stability. Previous research has also found that of the vectors of vertical wind shear and storm motion work together to determine TC rainfall patterns.

In this research, total precipitable water (TPW) surrounding TCs is analyzed along with vertical wind shear and storm motion to investigate their influence on the symmetry of TC rainfall at the time closest to landfall. The 43 storms that made landfall over the Gulf states in the U.S. from 1998 to 2015 are analyzed. A Geographic Information System is used to examine the TC rainfall patterns to determine if they are symmetrically distributed on each side of the storm. The amounts of TPW on the left side and the right side of the
storm are compared for 24 hours prior to landfall to determine if they are significantly different according to the results of Mann-Whitney $U$ Tests. In addition, the shortest distance between a contour line representing 40 mm of TPW and the storm center was calculated to determine the proximity of the non-tropical air mass. Finally, the vector of the vertical wind shear was analyzed in conjunction with the storm motion vector.

The results show that TC rainfall patterns vary regionally, and these variations are related to moisture conditions, vertical wind shear and storm motion. TCs that made landfall over the western Gulf states usually produced more rainfall on the right side of the storm, and the rainfall patterns are influenced by not only shear/motion but also the dry air mass from the continent. For TCs that made landfall over the central Gulf states, storms usually produced more rainfall on the right side of the track, and the vertical wind shear is the main factor influencing the rainfall distribution. Many storms among those that made landfall over the Florida peninsula produced more rainfall on the left side of storm due to enhanced convergence along a moisture boundary. In addition, the distance of $< 330-340$ km between a storm center and TPW values of 40 mm was a threshold for interaction between the moist air mass from the TCs and a frontal boundary behind which a more dry and cool air mass was found.
According to the National Hurricane Center (NHC), tropical cyclones (TCs) generally are defined as organized rotating low pressure systems of clouds and thunderstorms on the synoptic scale. TCs develop over tropical or subtropical oceans when environmental conditions are ideal, including low amounts of vertical wind shear, high sea surface temperatures (SSTs), low level positive vorticity and high moisture content in the lower and middle troposphere (Gray 1968). When generated over the Atlantic basin, TCs are classified according to their maximum sustained winds: tropical depression (< 38 mph, 33 knots), tropical storm (> 39 mph, 34 knots, < 73 mph, 63 knots), hurricane (> 74 mph, 64 knots), and major hurricane (> 111 mph, 96 knots). On average, 13 Atlantic tropical storms and hurricanes have occurred per year in the twenty-first century (Landsea et al., 2010).

During the development cycle of TCs over the ocean, the low-pressure region near the surface causes convergence of air which rotates counterclockwise in the northern hemisphere due to the pressure gradient force (PGF), the Coriolis force, centrifugal force and friction. As TCs intensify, their wind speeds increase which enhances evaporation of warm ocean surface water, and convergence forces the warm moist air to arise. The moisture-laden air spirals upwards near the storm center and condensation creates clouds in a band about 10–20 km wide. There is a warm core inside of the TC due to latent heat exchange as the air cools with height (Emanuel, 2003; Frank, 1977). In addition, the condensed moisture releases the latent heat into the atmosphere, causing the air to expand outside away from the TC center, causing divergence at the upper levels. Eventually, the air above the storm center begins to sink to the surface, causing the formation of an eye, which is a region about 5–50 km in radius with calm winds and a
clear sky (Frank, 1977). Outside the eyewall, spiral rain bands are observed, with deep convective cells and stratiform precipitation (Willoughby 1978, Barnes et al., 1990). The rain bands are formed near the eyewall first and propagate hundreds of kilometers outward (Senn and Hiser, 1959) in regions where moisture convergence occurs. The size of Atlantic basin TCs as measured by the radius of the outermost closed isobar varies 55–1030 km, and 90% of TCs are observed to be less than 555 km in radius (Kimball and Mulekar, 2004). In addition, Matyas (2010b) revealed that the edges of hurricane rain fields are located within the size of the radius of the outermost closed isobar from 90% of the TC observations between 1998 and 2008, and Guo and Matyas (2016) showed that TC rain fields are correlated positively with TC size as measured by the radius of gale-force winds.

When the center of a TC moves across the coast and over the land surface, it is classified as having made landfall. After landfall, TCs may dissipate depending on the surface roughness and depletion of evaporation for the storm’s core. Over the land, the increase of surface roughness enhances the moisture inflow of the boundary layer into the storm’s core, leading more convection and precipitation. However, this increased updraft causes stronger adiabatic cooling. In addition, the inefficiency of the land surface evaporation and the dry air advection from the continent into storm core leads to the depletion of humidity and latent heat exchange, inhibiting the production of precipitation, ultimately leading to decay (Tuleya and Kurihara, 1978).

If TCs move into the mid-latitudes, they can undergo extratropical transition (ET) by interacting with an upper-level trough and the polar jet stream. The ET process causes TCs to lose their warm core and gain the characteristics of an extratropical storm, and the process can be divided into two stages, transformation and reintensification stages.
During the transformation stage, TCs interact with the baroclinic system in the mid-latitudes, translation speed increases, storm intensity decreases, and the structure of the storm is distorted. A baroclinic zone, defined by National Oceanic and Atmospheric Administration (NOAA), is a broad region where a thermal gradient exists on a constant pressure surface, and it is associated with vertical wind shear which is referred to as a difference of wind speed and/or direction between the higher-level and lower-level atmosphere. Afterward, some storms may dissipate while others may experience the reintensification stage. In the reintensification stage, a transformed TC reintensifies by interacting with the upper-tropospheric divergence and positive vorticity advection (PVA), developing a cold core and frontogenesis (DiMego and Bosart, 1982; Foley and Hanstrum, 1994; Klein et al., 2000; Matano and Sekioka, 1971; Palmen, 1958). It usually takes 1-3 days for storms to complete ET (Matyas 2010a; Kitabatake 2011; Zagrodnik and Jiang 2013). Climatologically, the transition of Atlantic TCs happens frequently between the latitudes of 30° and 50° N, and between 1950 and 1996, 46% of Atlantic TCs experienced an ET phase (Hart and Evans, 2001). Among TCs that have made landfall over Florida since 1998, almost 60% of them completed an ET (Matyas 2014). When transitioning into an extratropical cyclone, TC rain fields become asymmetrical and disperse away from the storm center (Zick and Matyas 2016) but may continue to grow in areal coverage (Atallah et al. 2007; Matyas 2013; Zhou and Matyas, 2017), thereby producing rainfall far inland from the point of landfall. However, not all TCs dissipate or transform into extratropical cyclones after making landfall. For example, Tropical Storm Erin (2007) re-intensified due to moist soils from heavy rainfall, which increased water vapor and evaporation in the boundary layer, providing the latent heat exchange necessary to regenerate the low-pressure center. (Anderson and Shepherd, 2013; Kellner
When TCs make landfall, they can cause many casualties from high rainfall totals, flash floods, strong winds, and storm surges, and tornadoes (Rappaport, 2000. Rappaport, 2014). Water-related incidents from Atlantic TCs accounted for roughly 90% of the total deaths for the 50-year period from 1963 to 2012, and rainfall-induced freshwater floods and mudslides were responsible for 27% of the total deaths for the same period (Rappaport, 2014). In response to global warming, several numerical simulations suggest that storm intensity and TC rainfall rates will increase, although the overall frequency of TC events will decrease (Knutson and Tuleya, 2004; Knutson et al., 2010; Knutson et al., 2013; Trenberth 2005; Zhao and Held, 2012). In addition, the economic damage caused by TCs is expected to increase and be concentrated in North America by the year 2100 due to infrastructure and housing growth in the coastal zone (Mendelsohn et al., 2012). Therefore, it is important to have a better understanding of TC precipitation and its spatial patterns to reduce vulnerability and increase resilience against natural hazards caused by TC activity.

Many studies have been done to find which factors influence TC rainfall and its distribution patterns to improve the accuracy of TC rainfall prediction. TC rainfall and its distribution are influenced by various factors, such as vertical wind shear, storm motion, storm intensity, topography, ET, and moisture availability (Chen et al., 2006; Knutson et al., 2004; Lonfat et al., 2004; Lonfat et al., 2007; Matyas, 2008).

Vertical wind shear and TC motion are critical factors that produce asymmetrical rain fields. High vertical wind shear has an impact on TC structure, tilting the TC vortex and causing the upward motion on the downshear side of the eyewall which is tilted to the surface and downward motion on the upshear side. Also, storm's cyclonic motion can
transport moisture in counterclockwise rotation. Therefore, storms are likely to have more rain on the downshear left side (Chen et al., 2006; Corbosiero and Molinari, 2002; DeMaria, 1996; Jones, 1995; Matyas, 2010b; Raymond, 1992). In addition, a short time lag of less than 6 hours exists for vertical wind shear to influence TC rainfall distribution (Wingo and Cecil 2010).

The asymmetrical distribution of TC rainfall can be influenced by a TC’s motion as well. It is found that heavier rainfall could be produced on the front to front-right quadrants of TC motion. This is because frictional updraft and winds are stronger at the front of the storm, enhancing low-level convergence in the TC boundary layer (Corbosiero and Molinari, 2003; Lonfat et al., 2004; Shapiro, 1983). As a result, TCs that have faster translation speed than those with slower translation speeds experience stronger frictional convergence, resulting in a larger rainfall asymmetry (Corbosiero and Molinari, 2003; Lonfat et al., 2004; Matyas, 2010a). When strong vertical wind shear (> 5 m s\(^{-1}\)) is across the storm motion, the combined motion (front right) and shear (downshear left) components overlap, causing storms to produce an asymmetrical rainfall distribution. However, if vertical wind shear is weak (< 5 m s\(^{-1}\)) and along the track, the storm produces a symmetrical rainfall distribution across the front side of the storm (Chen et al., 2006).

TC intensity is another factor that can influence the spatial distribution of TC rainfall. More intense TCs have stronger vorticity that produces more swirling winds and convection, resulting in stronger storm structure with more symmetrical rainfall patterns than less intense TCs. Also, this stronger spiral wind can transport and redistribute more precipitation around the entire storm. As a result, the distribution of TC rainfall is likely to become broader while TC intensity increases (Lonfat et al., 2004; Rodgers and Adler,
1981). Previous studies have confirmed that at maximum intensity, TCs have the most circular, compressed, and symmetrical distribution of clouds and rainfall (Dvorak 1975, Zick and Matyas 2016).

Topography is also related to TC rainfall. Strong orographic lifting is often generated on the windward side of mountains. When TCs pass over a mountain range, their vorticity advection upstream is enhanced by the orographic effect, causing heavy rainfall on the windward side (Lin and Savage, 2011) For example, Hurricane Camille (1969) produced up to 686 mm of rainfall in one place during 12 hours along the slope of the Appalachian Mountains in central Virginia (Schwarz, 1970). However, even small changes in elevation such as that occurring near the Edward’s Plateau in central Texas can enhance precipitation as a TC passes nearby (Matyas 2007). In addition, topographic barriers can also block low-level moisture, reducing the moisture supply for TCs (Bender et al., 1985; Schubert et al., 1998).

TC rainfall patterns can be impacted by ET process (Atallah and Bosart, 2003). In the case of Hurricane Floyd, the rainfall distribution was influenced by a mid-latitude weather system during ET. The cool and dry air mass from a mid-latitude trough met the warm and moist air masses of Floyd, producing a tropospheric-deep baroclinic zone. This new environment changed the structure of Floyd, and therefore, the heaviest rainfall was produced on the left side of the storm (Atallah and Bosart, 2003). Although rainfall decreases behind the storm center, isentropic uplift such as warm air advection in the broad area ahead of the storm can cause the total raining area to increase during the ET process (Matyas 2013) and be more dispersed away from the storm center (Zick and Matyas 2016).
Moisture and its phase change are one of the most important factors in producing clouds and precipitation. As a result, it is important to understand the linkage between the moisture availability around TCs and the amount of TC rainfall or TC rainfall patterns. For example, sea surface temperatures (SSTs) are related to moisture availability. Higher SSTs produce more water vapor in the lower troposphere, generating more energy for atmospheric convection, which is associated with thunderstorm clouds. Therefore, TC rainfall rates are likely to increase in the vicinity of higher SSTs due to more water vapor in the atmosphere (Holland, 1997; Knutson et al, 2010; Trenberth, 2005). Matyas and Cartaya (2009) also found that increasing atmospheric moisture surrounding the storms that traveled with a slow forward velocity caused increased rainfall accumulation when contrasting Hurricanes Frances (2004) and Jeanne (2004) during their passage over Florida.

Encountering a relatively dry continental air mass can limit rainfall production and/or cause an asymmetrical rainfall pattern to develop. For TCs approaching land in the northern hemisphere, more rainfall was produced on the right side of the storm, and the shape of the rain field was asymmetrical due to dry air intrusion from the land (Chan et al., 2004; Kimball, 2008). This is because the relatively dry air at the low level from the continental land mass surrounds the TC from the left and penetrates into the storm at higher altitudes. As a result, atmospheric stability on the left side of the storm increases, inhibiting convection development, and instability of the right side increases with more convection, causing an asymmetry in rainfall distribution. Also, modeling and observational studies have shown that TCs can reach greater sizes when environmental moisture surrounding the storm is relatively high (Hill and Lackmann 2009, Matyas and Cartaya 2009, Matyas 2010b). Furthermore, a time lag exists between an increase in
available moisture and increase in TC rainfall production. Jiang et al. (2008) found that there is a 12-hour time lag between volumetric rain and the combination of maximum TC wind speed and total precipitable water (TPW), and Matyas (2010) also found a 12-hour lag between changes in relative humidity and rainfall extent in hurricanes making landfall along the U.S. coastline.

Due to the complicated TC structure and its production of rainfall it is still difficult to get an accurate forecast of rainfall from TCs in coastal areas (Jiang et al., 2008; Villarini et al., 2011). Relatively few studies have examined environmental moisture conditions surrounding TCs during landfall and no previous research has investigated the symmetry of TC rainfall in conjunction with moisture distribution and vertical wind shear/storm motion components according to the location of U.S. landfall.

Jiang et al. (2008c) found that TPW can be used as a parameter of moisture conditions to improve the accuracy of TC rainfall prediction. It is defined as the total water vapor in a column of the atmosphere from the surface to the top of the atmosphere and it is a part of the moisture budget. As a result, many studies have used TPW to examine the relationship between atmospheric moisture and TC rainfall. Rogers and Pierce (1995) found that TPW was associated with the precipitation distribution in the case of Typhoon Bobbie 1992. The influx of moist (TPW greater than 50mm) or dry air into Typhoon Bobbie 1992 initiated or reduced convective rain bands in its outer-core region. Jiang et al. (2008a, 2008b) investigated the cases of Hurricane Isidore (2002) and Lili (2002) by using moisture budget as well. They found that Isidore had more rainfall and larger rain fields than Lili, because Isidore was wetter and its environment had more humidity. Also, in the two cases, they found that moisture convergence and TPW are very important factors to produce and maintain the heavy rainfall before a TC makes landfall. Another
study by Jiang et al. (2008) revealed that TC rainfall over both land and ocean is highly correlated with the combination of TPW and TC maximum wind speed, while TPW and proximity to land were the key predictors of TC rainfall over Puerto Rico as discovered by Hernandez and Matyas (2016). Due to the importance of the TPW, it even has been used to study the frequency of TC formation (Matyas, 2015).

Therefore, this research investigates how the spatial patterns of TC rainfall differ according to the TPW spatial patterns surrounding the TCs as well as variations in topography, vertical wind shear and storm motion. This research has three main steps. First, the spatial patterns of TPW surrounding each TC are measured and compared regionally to find a linkage between the distribution patterns of TC rainfall and the TPW conditions. The second step is to analyze the regional variations in the speed and direction of the vertical wind shear vector and its influence on the symmetry of TC rainfall distribution. Third, the symmetry of TC rainfall at the time closest to landfall are measured and compared among different landfall regions along the U.S. Gulf Coast. The main hypothesis is that the spatial pattern of TC rainfall at the time closest to landfall will differ according to the spatial pattern of TPW and the vectors of vertical wind shear/storm motion and that these conditions vary regionally across the U.S. Gulf Coast.

This study examines 43 storms attaining at least tropical storm intensity during 24 hours before the time closest to landfall from 1998 to 2015. A Geographic Information System (GIS) is mainly utilized to analyze the data of TC tracks, TC rainfall patterns and TPW conditions. The Mann-Whitney U Tests are calculated to test the hypothesis. Figure 1-1 shows the study area of this research. In Chapter 2, the data and the research methods are explained with details. Also, results will be discussed. Chapter 3 consists of
the TC research in Geography, the summary of the research, the contribution to literature, and the future research plan.
Figure 1-1. The study region within the Gulf of Mexico and the Gulf coastal states in the U.S.
CHAPTER 2
THE INFLUENCE OF MOISTURE, VERTICAL WIND SHEAR AND STORM MOTION ON THE RAINFALL DISTRIBUTION PATTERN OF TROPICAL CYCLONES IN THE SOUTHERN GULF COASTAL STATES

Introduction

Tropical cyclones (TCs) are one of the most destructive and dangerous single events in the atmosphere as they can bring strong winds and heavy rainfall when moving over land. In the history of Atlantic TCs from 1963 to 2012, water-related hazards from TCs were responsible for approximately 90% of the total deaths, and 27% of deaths were associated with freshwater floods and mudslides caused by heavy rainfall from TCs (Rappaport, 2014). By the year 2100, it is expected that the financial damage caused by TCs will increase and will be concentrated in North America, causing approximately $26 billion damage per year due to population and income growth in the coastal regions (Mendelsohn et al., 2012). Although forecasts of TC tracks have improved significantly (McAdie and Lawrence, 2000), the forecast of TC rainfall in coastal areas still remains a difficult problem due to the complicated process of precipitation formation in TCs (Jiang et al., 2008c; Villarini et al., 2001).

To improve TC rainfall forecasts, it is important to understand the processes that control the spatial distribution of rainfall about the storm center. Through both modeling and observational studies, previous researchers determined that environmental factors such as vertical wind shear, storm motion, storm intensity, topography, extratropical transition (ET), and moisture are key components that contribute to TC rainfall patterns (Chen et al., 2006; Jiang et al., 2008a; Knutson et al., 2004; Lonfat et al., 2004; Lonfat et al., 2007; Matyas, 2008).

Literature Review

Vertical Wind Shear and Storm Motion
High vertical wind shear and storm motion are the dominant factors for asymmetrical TC rainfall distribution (Corbosiero and Molinari 2003; Chen et al., 2006, Rogers et al. 2003). Vertical wind shear tilts the vortex of TCs as faster winds occur in the upper troposphere and slower winds exist in the lower troposphere. As the vortex adjusts to the tilt, upward motion is generated on the downshear side in which the direction of tilted axis faces to the surface with downwind, enhancing more convection near the eyewall and propagating cloud and precipitation outward, while downward motion is enhanced on the upshear side which limits rainfall production, resulting in more rainfall on the downshear side (Chen et al., 2006; Corbosiero and Molinari, 2002, 2003; DeMaria, 1996; Jones, 1995; Matyas 2010b). Chen et al (2006) also revealed that if the speed of vertical wind shear exceeds of 5 m s$^{-1}$, TC rainfall patterns are likely to be influenced by vertical wind shear regardless of storm motion. If not, the rainfall patterns are determined by storm motion, more rainfall on the front to front-right side of vortex due to stronger frictional convergence ahead of the storm (Corbosiero and Molinari, 2003; Lonfat et al., 2004; Matyas, 2010a).

**Tropical Cyclone Intensity**

In addition, TC rainfall patterns are also influenced by TC intensity. If TC intensity increases, the storm’s cyclonic motion becomes faster and stronger, forcing more swirling wind upwards with a better-developed storm structure that produces more symmetrical rainfall patterns. In addition, TC rainfall distributions become wider because rainfall can be redistributed by stronger spiral winds. However, weaker TCs produce more asymmetrical rainfall patterns (Lonfat et al., 2004; Rodgers and Adler, 1981).

**Topography**
Topography can cause either heavy rainfall or less rainfall from storms. Lin and Savage (2011) found that a storm can produce more heavy rainfall on the windward side when the moisture transported by the storm that approaching to land is blocked by mountains. As a result, if moisture influx from the Gulf of Mexico is blocked by topographic barriers such as North America Cordillera, moisture convergence can occur with the dry or cool air mass from the continent, causing heavy rainfall over Great plains in the U.S. (Schubert et al. 1998). However, the topographic barriers can inhibit low-level moisture transport from the west side of mountains to Texas or the east side of Mexico (Bender et al., 1985, Schubert et al., 1998). Therefore, moisture supply can be limited for the left side of the storm that making landfall over Texas.

**ET process**

TC rainfall patterns are also influenced by the ET process. If TCs move into the mid-latitudes, they can transform into extratropical cyclones by interacting with a mid-latitude weather system such as upper-level trough or a frontal boundary (DiMego and Bosart, 1982: Foley and Hanstrum, 1994; Klein et al., 2000; Matano and Sekioka, 1971; Palmen, 1958). The interaction between the cool and dry air mass from a mid-latitude trough and the warm and moist air mass from TCs produces a deep baroclinic zone that provides a mechanism for convergence and uplift of tropical moisture that promotes heavy rainfall on the left side of the storm (Atallah and Bosart, 2003). In the new environment, TCs are transformed by increasing the storm speed, decreasing TC intensity and having distorted storm’s structure, resulting in the loss of warm core. Afterward, if TCs interact with the upper-tropospheric divergence and positive vorticity advection (PVA), a cold core and frontogenesis is developed instead with isentropic uplift
in the broad area ahead of the storm. As a result, the rain field is more dispersed away from the storm center (Zick and Matyas 2016).

**Moisture**

A sufficient supply of moisture in the atmosphere is required for TC formation and rainfall production. Although TCs are driven by gaining energy from the evaporation of moisture in the boundary layer (Elsner and Kara, 1999; Frank 1977), there has been a limited amount of research examining the relationship between moisture and TC rainfall distribution patterns during and after landfall. TCs can produce asymmetrical rainfall patterns when they approach land due to the influx of dry air mass (Chen et al., 2004; Kimball, 2008). When the drier air from the continental land masses flows counterclockwise around the left side of northern hemisphere TCs and penetrates into the TC core, the atmospheric instability on the left side decreases, which limits rainfall production. However, storms can gain large amounts of moisture over warm ocean waters from their equatorward side as they approach land, and the moisture increases instability and rainfall production on the right side of the storm. As a result, TCs may produce less rain on the left side and more rain on the right side when encountering a somewhat drier continental air mass ahead and left of its circulation center. Therefore, it is important to examine the amount and spatial distribution of moisture to better predict where a TC will produce rainfall once over land.

**Tropical Cyclone Rainfall and Total Precipitable Water**

Jiang et al. (2008c) suggested that the accuracy of TC rainfall forecasts can be improved by using total precipitable water (TPW) as a parameter of moisture conditions. TPW is the total water vapor in a column of the atmosphere from the earth's surface to the top of the atmosphere. The amount of TPW over regions where TCs form is
approximately 40-50 mm globally (Chu 2002; Inoue et al., 2002; Matyas 2015). Rogers and Pierce (1995) revealed that the influx of moist (TPW greater than 50 mm) or dry air (TPW less than 50 mm) surrounding Typhoon Bobbie 1922 was related to the precipitation pattern by initiating or reducing convective rain bands in its outer-core region. Jiang et al. (2008a, 2008b) assessed the moisture budgets of Hurricanes Isidore (2002) and Lili (2002). They found that Isidore produced more rainfall than Lili because the environment for Isidore was wetter and TPW was crucial for the moisture convergence needed to produce heavy rainfall from large-sized TCs. Hernandez Ayala and Matyas (2016) showed that TPW and proximity to land were responsible for variations in TC rainfall totals and their spatial patterns over Puerto Rico.

Because a TC must gather moisture from a large radius (Trenberth et al. 2003) and moisture converges towards the TC center to generate its rain fields, there is a lag between the onset of increased or decreased moisture in the TC’s surrounding environment and its effect on rainfall production. Jiang et al. (2008c) found that the combination of TPW and TC maximum wind speed is highly positively correlated with TC rainfall over land and ocean with 12-hour time lag between TPW and TC rainfall. Therefore, it is important to examine how the amount of available moisture changes as a TC approaches land to predict the rainfall pattern.

Although it has been established that TPW is an important component of TC precipitation production, no previous research has studied the symmetry of TC rainfall in conjunction with TPW distribution patterns for the TCs that made landfall over the U.S. The moisture content of air masses present over the southern U.S. differs regionally, becoming increasingly wetter toward the east (Thornthwaite 1931). Also, more moisture exists over the ocean than the land (Trenberth et al., 2011). The distribution of TPW
varies according to whether a TC moves into a hot and dry continental air mass, or encounters a relatively cool and dry air mass associated with a middle latitude trough or a frontal system.

**Research Objectives**

Given the spatial variation of moisture in the southern U.S. and the importance of moisture for rainfall production in TCs, the main objective of this research is to investigate whether symmetrical or asymmetrical patterns of volumetric rainfall develop with respect to the left and right side of the storm as they make landfall over the Gulf Coast of the U.S. and whether these patterns coincide with the spatial distribution of TPW as well as the vectors of vertical wind shear and storm motion. We examine with the amount of TPW on each side of the storm and measure the distance between the storm center and the contour line representing 40 mm of TPW to determine if a different air mass exists close to the storm’s circulation. As the direction of storm motion influences where rainfall develops with respect to the storm center and motion vectors vary regionally in Gulf of Mexico shifting from northwest to northeast direction toward the east (Ho et al., 1987), the 43 TCs examined are placed into three groups based on the landfall location and the storm motion direction (Figure 2-1, Table 2-1, 2, 3). The data for the amount of volumetric rainfall at the time closest to landfall and spatial characteristics of TPW during the 24 hours prior to landfall are analyzed within a Geographic Information System (GIS). The results of Mann-Whitney *U* tests reveal whether TCs in each landfall location group have different median values of moisture and volumetric rainfall, and whether these relationships change during the 24-hour period surrounding landfall. Less moisture should be present on the left side of TCs that made landfall over the western and central Gulf Coast due to the dry continental air mass causing less rain on the left side of the TCs.
However, more moisture should surround TCs and rainfall should be more symmetrically-distributed ahead of TCs that made landfall over the eastern Gulf because the Florida peninsula is so narrow that moisture can be supplied from the Atlantic Ocean, creating a more symmetrical rainfall pattern.

The second goal is to determine how frequently the relationship between vertical wind shear and storm motion accounts for the spatial pattern of rainfall along with or in spite of the spatial distribution of moisture. The atmospheric flow has a strong westerly or southwesterly component over the study region during the hurricane season, meaning that rainfall should be enhanced east and north of the storm center (Corbosiero and Molinari 2003, Goldenberg and Shapiro, 1996). All TCs examined have a strong northward component to their motion, with TCs in the west Gulf having a stronger westward component and those in the east Gulf a stronger eastward component. If the directions of storm motion and vertical wind shear are compared, the angle difference should vary regionally to produce more rainfall on the right side of the storm in the west and central Gulf, but similar directions of shear and motion vectors for TCs in the east Gulf should lead to rainfall that is either symmetrical or left of the storm center. Mann-Whitney U tests are conducted to test these hypotheses as well.

**Data and Methods**

**Tropical Cyclone Datasets**

Data from the Tropical Rainfall Measuring Mission (TRMM) 3B42 product were utilized to determine if TC rainfall was distributed symmetrically or asymmetrically on the left or right side relative to TC track at the time closest to landfall. Three-hourly data pertaining to rain rates are available since January 1998. Therefore, the period of study from 1998 to 2015 was chosen due to the availability of TRMM data. The 3B42 dataset is produced by combining both microwave and infrared precipitation estimates from the
TRMM satellite (Huffman et al., 2007). The products are improved by adding rain gauge data, ground-based radar data, and data from other satellites (Huffman and Bolvin, 2012). The TRMM dataset covers areas from 50°N to 50°S in latitude and 180°W to 180°E in longitude, with 0.25° x 0.25° pixels as the spatial resolution, which is approximately 27 km at the equator. This dataset has the limitation that high rain (>5 mm hr⁻¹) is underestimated and light rain (≤1 mm hr⁻¹) is overestimated over the land and the ocean (Chen et al., 2013). In addition, the rain rate is measured differently over the ocean and the land because two different algorithms are employed (Kummerow et al., 2001).

TPW data were obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger et al., 2006), derived from the National Oceanic and Atmospheric Administration’s (NOAA) National Centers for Environmental Prediction (NCEP) Eta Model with the Regional Data Assimilation System (RDAS) using historical observations across the North American region. The spatial resolution is about 0.3° which is 32 km at the lowest latitude (1° N). The temporal resolution is 3 hourly from January 1979 to the present, and the unit of TPW is mm or kg m⁻² which is the instantaneous amount at the time. Zick and Matyas (2015 a, b) showed that since 1998, this reanalysis dataset is competitive in TC research by comparing TC position and structure with another reanalysis dataset and by comparing TC precipitation with TRMM 3B42.

Vertical wind shear data were obtained from the Statistical Hurricane Intensity Scheme (SHIPS) database of NCEP Global Forecast System (GFS) model analysis (DeMaria et al., 2005). The wind vectors between 200-800 km radius from storm centers are averaged and the vector differences between 850 and 200 hPa are computed for the wind speed and the direction. As vertical wind shear values are only available with 6 hourly temporal resolution at UTC 00, 06, 12, and 18, the data were interpolated lineally
every three hours to match with the TRMM and NARR data sets (Matyas 2013). However, wind shear data from SHIPS stopped before the time closest to landfall for several storms (Earl 1998, Mitch 1998, Harvey 1999, Gordon 2000, Matthew 2004, and Barry 2007). The available data from the time closest to landfall (3-6 hours away in most cases) was used for these storms because the vector of wind shear was fairly consistent over the 24 hours leading up to the final observation.

The International Best Track Archive for Climate Stewardship (IBTrACS) was used to determine the position and intensity of each TC (Knapp et al., 2010). IBTrACS provides the position of the storm center and storm intensity every six hours (00, 06, 12, and 18 UTC). As the TRMM and NARR data sets have a three-hour temporal resolution, TC positions were lineally interpolated every three hours to match these datasets. In addition, previous research has shown that there is a time lag of 12-24 hours for the influence of environmental conditions on TC structure (Jiang et al., 2008c; Matyas, 2010b). Therefore, this study examined environmental moisture at landfall and during the preceding 24 hours. Time periods were designated as landfall 00 (t00), and 3 (t03), 6 (t06), 9 (t09), 12 (t12), 15 (t15), 18 (t18), 21 (t21), and 24 (t24) hours before landfall. TCs that formed over the Gulf of Mexico less than 24 hours prior to landfall were not examined. The direction and speed of the storm motion was determined by the TC’s position over the preceding three hours. For example, the TC direction 12 hours prior to landfall (t12) was decided by the TC position at t12 and t15.

Methods

The 43 storms (Table 2-1, 2, 3) were divided into three groups based on landfall location and storm motion to investigate if rainfall patterns varied regionally as should moisture and the difference between shear and motion vectors. The first group contained
12 landfalls occurring over Texas, where TCs tended to track towards the northwest before landfall. The 17 landfalls in Central Group included TCs with the strongest northward component to their motion. Here, landfalls spanned Louisiana, Alabama, Mississippi, and northwestern Florida. Florida was divided into two regions along 86°W longitude due to its unique shape. On the west side of 86°W, TCs with motion vectors between north-northwest and north-northeast directions were included in Central Group. However, east of 86°W, most TCs had tracks with stronger eastward motion. Therefore, Eastern Group contained 14 landfalls occurring on the Gulf of Mexico side of Florida on the east side of 86°W longitude (Figure 2-1).

A Geographic Information System (GIS) was utilized to plot and analyze data obtained from IBTrACS and NARR during the 24 hours before t00, and TRMM data at t00. These data were transformed into an equal-area projection: North America Albers Equal Area Conic.

The first step was to measure the TPW around each TC (Figure 2-2). Trenberth et al. (2003) found that rainfall-producing weather systems typically gather water vapor from a distance approximately 4x the radius of the precipitating region. As the average rain field extends 223 km from the storm center at the time closest to landfall (Matyas, 2010b) and the average rainfall region extends approximately 240 km from the storm center on the day of landfall (Zhou and Matyas, 2017), 250 km was used as an average radius of a TC rain field at landfall and this equated to a radius of 1000 km for the incorporation of environmental moisture. This study centered a 3 x 3 grid on the TC’s position that was oriented parallel to the storm’s trajectory to measure moisture on the left and right side of the storm within the 1000 km radius. Each box had a 500 km length and a 500 km width; thereby measuring 750 km left, right, in front of, and behind the TC, and measuring 1060
km, northwest, northeast, southwest, and southeast of the TC. This method facilitated dividing the atmosphere surrounding the TCs into octants, and measuring TPW only on the left and right side of the storm to determine if there was less moisture on the left side due to a dry air intrusion from the continent as tested by Kimball (2008). The grid cell in the upper left corner was labelled as Cell 1, while the grid box containing the TC center was Cell 5. The amount of TPW was measured in the nine boxes every three hours at t00, t03, t06, t09, t12, t15, t18, t21, and t24 (Figure 2-2). A cell in a grid consisted of approximately 280 pixels. The values of TPW for each pixel in a cell were summed, and an average TPW amount of each grid cell was calculated. Then, the amount of TPW in cells 1, 4, and 7 (3, 6, 9) were averaged to determine the amount of moisture on the left (right) side of the storm. The values of TPW on each side were compared using the Mann-Whitney U test to determine if they were significantly different.

Previous studies have indicated that TPW values above 40 mm indicate that the environment is favorable for TC formation and heavy rainfall (Chu 2002; Farfan and Fogel 2016; Inoue et al., 2002; Matyas 2015). Therefore, the TPW value of 40 mm was contoured, and the shortest distance between it and the storm center was measured to determine how close the relatively dry air mass from the continent existed to the storm center. Storms that transformed into extratropical cyclones should be closer to the boundary between the moist air mass surrounding the TC and relatively cool and dry air mass associated with a trough or frontal boundary. More rainfall should be produced on the left side of the storm where the two air masses converge. In addition, the measured distances were compared by regional groups and rainfall distribution patterns (Figure 2-9, 10).
The next step was to define the symmetry of the rainfall patterns. To define the areas receiving moderate rainfall, the outer edges of the rain fields were contoured using a rain rate of 5 mm hr$^{-1}$ as a threshold defined by Zagrodnik and Jiang (2013). The regions enclosed by contours of 5 mm hr$^{-1}$ were transformed into polygon features, and the areas of the polygons were measured. Polygons which were located within or that intersected with a 250 km buffer zone from the TC center were selected and used to calculate the volumetric rainfall on the right and left side of the storm at t00 by multiplying the mean value (mm hr$^{-1}$) of rain rates within the selected polygons by the area (km$^2$) of selected polygons (Figure 2-3). The rainfall patterns were classified into one of three groups according to the amount of volumetric rainfall on each side of the storm. If the difference of the percentage of volumetric rainfall between on the left side and the right side of storm was less than 20% of the total amount of volumetric rainfall, this was deemed as being a Symmetrical (S) pattern (Figure 2-4a). For the remaining cases, the asymmetrical rainfall patterns were distinguished into two categories. If the volumetric rain on the TC’s left side was equal to or greater than 60% of the total, it was defined as AL, which means an asymmetrical pattern with more rain on the left side (Figure 2-4b). In contrast, if the volumetric rain on the TC’s right side was equal to or greater than 60% of the total, it was defined as AR, meaning an asymmetrical pattern with more rain on the right side (Figure 2-4c). The volumetric rain values on either side were compared between each regional group using Mann-Whitney $U$ tests.

Another step was to compare the distribution of the volumetric rainfall at t00 and TPW conditions during 24 hours before t00 by region to examine how moisture conditions varied from west to east among the three groups. The continental air mass should be driest for Texas landfalls because the west side of Texas is arid. Therefore, average
TPW, distance to TPW contour line of 40 mm, and the amount of rainfall should be lowest in Western Group. However, landfalls in the eastern part of the study region might have been more influenced from oceanic air masses because most of Florida is surrounded by the ocean. Therefore, average TPW, distance to TPW contour line of 40 mm, and rainfall should be highest in Eastern Group when ET cases are not considered. In this study, the rainfall pattern at t00 was compared to the amount of TPW on the left and right side of the storm during 24 hours before t00, following Kimball’s study (2008). If less moisture exists on the left side of the storm (Cells 1, 4, and 7) than the right side (Cells 3, 6, and 9) due to the continental air mass, there should be lower average rainfall on the left side of the storm than on the right side, which is an AR pattern. If the amount of moisture on either side is not different due to the moisture influx from Atlantic Ocean and Gulf of Mexico, storms should produce symmetrical rainfall distribution, which is a S pattern. If storms produce more rain on the right side of the storm than on the left side, it is defined as an AL pattern. To test these hypotheses, the Mann-Whitney U tests were calculated to compare TPW conditions on the left side versus the right side of the storm within each group to determine whether statistically significant differences in moisture existed. In addition, TPW conditions on the left (right) side of the storm were compared in pairs for the three regional groups using the Mann-Whitney U tests to examine if there were different moisture conditions depending on regions. The null hypothesis was that TPW is similar on both sides of the TCs and between the groups.

The final step was to analyze the angle difference between the directions of storm motion and vertical wind shear at t00 to apply it to the distribution of rainfall. Potential time lags between the onset of wind shear and asymmetries in rainfall distribution were not considered because Wingo and Cecil (2010) revealed that a short time lag less than 6
hours exists between them. The angle between the vectors of storm motion and vertical wind shear were calculated for each storm by subtracting motion vector from shear vector and then an average was computed for each group (Figure 2-11). If the angle of vertical wind shear was different from the angle of storm motion between -15° and 45° or 165° and 225°, the vortex of storms would tilt ahead of or behind the direction of storm motion. Therefore, the rainfall would be distributed ahead or behind of storm symmetrically, creating a S pattern. If the angle of vertical wind shear was different from the angle of storm motion between 45° and 165°, it was assumed that the rainfall would exhibit an AR pattern. This is because the direction of wind shear is toward the right side of storm motion, and the vortex of storm tilts to the right side producing more rainfall on the right side. If the angle of vertical wind shear was different from the angle of storm motion between 225° and 345°, it was assumed that the storms would have an AL pattern because more rainfall could be produced on the left side due to the tilt of the vortex. If the shear speed didn’t exceed of 5 m s⁻¹, the motion component was more influential rather than shear component and thus an AR pattern would be produced. The Mann-Whitney U Tests were utilized to see if the distribution of angles between motion vector and shear vector was significant for each group (Table 2-8).

The Results

TPW Conditions

As the TCs approached landfall, the total amount of TPW for the eight grid cells surrounding the storms (Cells 1-4 and 6-9) decreased in all regions as the grid moved deeper into the continental air mass (Figure 2-5). When the total amounts of TPW across all analysis times were averaged by groups, a statistically significant difference in group median values existed between not only Western and Central Group, but also Central
and Eastern Group (Table 2-4). However, values did not increase from west to east as originally hypothesized, with the highest values belonging to TCs in Central Group (Figure 2-5).

In Western Group, the nearest edge of the 40 mm value of TPW was positioned in Cell 1 or 4 in 10 cases, and the distance to the TPW contour line of 40 mm was the smallest, averaging 521 km at t24 and averaging 349 km at t00 (Figure 2-9), causing the lowest averaged total TPW values among the three groups. The amount of TPW on the left side of the storm decreased as TCs approach to the land due to the continental air mass (Figure 2-6), while TPW on the right side of the storm remained constant due to the advection of the oceanic air mass from the Gulf of Mexico (Figure 2-7). As a result, the value for the amount of TPW on the right side was significantly higher than the TPW on the left side (Figure 2-6 &7, Table 2-7), suggesting there could be more rainfall on the right side which should produce the AR pattern.

In Central Group, the averaged total TPW values were the highest on both sides among the three groups (Figure 2-6 & 7). In addition, the average distance to the TPW contour line of 40 mm was much larger for TCs in Central Group, averaging 675 km at t24 and 490 km at t00 (Figure 2-9). This result suggests that either the storms were embedded in a larger pool of moisture, or that the continental air mass was not as dry as it was for Groups 1 and 3 (Figure 2-6, Table 2-7). Another explanation for the relatively high average TPW values for Central Group is that the outer reaches of the grid boxes did not encounter as much land on either side as did the other groups due to the width of the Gulf of Mexico. As a result, TPW conditions were similar on both sides of the storm (Figure 2-6 &7, Table 2-7), suggesting that rainfall should be symmetrical.

In Eastern Group, given the asymmetrical distribution of environmental moisture,
the distribution of TPW between the left and the right side was significantly different for
Group 3 from t24 until t00, suggesting the rainfall distribution should be the AR pattern
(Figure 2-6 &7, Table 2-7). The TPW contour line of 40mm was generally located much
closer to the storm center on the left (16 cases) than the right side (1 case) of the storm
at an average distance of approximately 483 km at t24 and 389 km at t00 which was
much closer than expected due to the fact that 11 out of 14 storms completed an ET
(Figure 2-9). Therefore, it was expected that the storms that completed ET should
produce the AL pattern.

Although Central Group had statistically significantly higher values of total TPW
surrounding storms than the other two groups, values for Groups 1 and 3 did not
significantly differ (Table 2-4). Also, the values of TPW on the left and the right between
Western and Eastern Group did not differ significantly (Table 2-5, 6). The main reason
for the similarity between Groups 1 and 3 for the values of TPW on the left side is that
the TPW contour lines of 40 mm were generally located closer to the storm center on the
left side (cell 1, 4 or 7) of the storm. The position of TPW contour line in Western Group
was due to the fixed location with topography in western Texas and Mexico such as the
North American Cordillera, which can block the influx of low-level moisture supply to TCs
(Bender et al., 1985; Schubert et al., 1998). However, 11 storms out of 14 in Eastern
Group completed an ET, while only 1 storm experienced an ET in Western Group. Due
to the favorable environment for storms to complete an ET for Eastern Group, the close
proximity of TPW contour lines on the left side are likely due to a frontal boundary in
Eastern Group. A visual inspection of surface analysis weather maps from NOAA on the
day of landfall for TCs in Groups 1 and 3 confirmed that the 40 mm TPW contour line
was generally linked to topography or dry continental air mass for Western Group and a
frontal boundary for Eastern Group. Therefore, in contrast to the expected AR pattern from TPW conditions surrounding the storms in Eastern Group, the frontal boundary or trough can be a focusing mechanism to trigger an AL pattern during the ET process.

**Vertical Wind Shear and Storm Motion**

The vertical wind shear and storm motion vectors at t00 were analyzed for each TC and each group. The averaged values of the vertical wind shear (storm motion speed) increased from west to east with 6.8 m s\(^{-1}\) (5.6 m s\(^{-1}\)) for Western Group, 11.3 m s\(^{-1}\) (5.9 m s\(^{-1}\)) for Central Group, and 16.1 m s\(^{-1}\) (7.5 m s\(^{-1}\)) for Eastern Group. The speeds of vertical wind shear for 39 storms among the 43 storms were high enough to influence the rainfall distribution as they were higher than the 5 m s\(^{-1}\) threshold established by Chen et al (2006). When the angles of vertical wind shear were compared to the angles of storm motion by regional groups, a statically significant difference existed between them in Western and Central Group (Table 2-8). The average angle difference was 136.8° for Western Group suggesting the rainfall should be right side of the storm to produce the AR pattern. The angle difference of 91.3° for Central Group also suggests that the AR pattern should be common. Lastly, the angle difference was 8.2° for Eastern Group (Figure 2-11). This generally suggests that storms that didn’t complete ET in Eastern Group should have rainfall ahead of storm motion which is considered as the S pattern and storms that completed ET should produce an AL pattern (Matyas 2010b).

**Rainfall Patterns**

The averaged total volumetric rain over the entire outlined area where the rain rate was greater than 5 mm hr\(^{-1}\) increased from West to East as expected (Figure 2-12), but it was not due to the first hypothesis that the more moisture can be supplied into the
storms in Eastern Group due to the oceanic environment. The averaged volumetric rain on the left and right side of the storm were compared within groups. In Groups 1 and 2, the Mann-Whitney $U$ test showed that there was a significant difference between the amount of rainfall on the left and right side of the storm, with more rainfall on the right side to produce the AR pattern. (Figure 2-13, Table 2-9). In fact, the majority of cases exhibited this pattern in both groups (Figure 2-14). In Eastern Group, the amount of volumetric rain between on the left and the right side didn’t differ significantly according to the Mann-Whitney $U$ Test, indicating more S patterns (Figure 2-13, Table 2-9).

However, the result of the rainfall distribution comparison between the left side and the right side of the storm for each storm in Eastern Group was different from the suggestion of Mann-Whitney $U$ Test result. In Eastern Group, 50% of storms had AL patterns because many cases completed ET (Figure 2-14).

**Rainfall Patterns by TPW, Vertical Wind Shear, and Storm Motion**

From the analysis of the distance to TPW contour line of 40 mm for the rainfall distribution patterns of 43 storms, the value for the storms that had AR or S pattern was clearly larger than for the storms that had the AL pattern, with a natural break of approximately 330-340 km (Figure 2-10). This result can be explained by the ET process. When a trough or a frontal boundary approaches close to the storm center from the left side of the storm, they bring a cooler and drier air mass from the middle latitudes. The cyclonic motion of air flow associated with a TC can transport the moist and warm tropical air mass to converge with the somewhat cooler and drier middle latitude air mass in the left front quadrant of the TC (Figure 2-8c). This process of interaction between two different air masses generates an advection for uplift and more rainfall in the region, producing an AL pattern, and the distance of 330-340 km should be the threshold for the
interaction. The storms that produced AL patterns generally completed ET less than 24 hours after t00.

Analyzed averaged TPW conditions and vertical wind shear conditions suggested there should be more AR patterns for Western Group. As expected, most storms had the AR pattern. There were two S pattern cases (Claudette 2003 and Ike 2008), and one AL pattern case (Edouard 2008). The rainfall distribution pattern of Claudette was matched well with both TPW and the shear/motion conditions. The values of TPW during 24 hours prior to landfall between the left and the right side were similar. The angle difference between motion vector and shear vector was $189^\circ$, suggesting the S pattern. In the case of Ike, the values of TPW between the left and right side were similar during 24 hours prior to landfall according to the Mann-Whitney $U$ tests. However, the angle difference between motion vector and shear vector was $84.3^\circ$, suggesting the AR pattern. Although Ike completed an ET 30 hours later from t00, the storm might not interact with a frontal boundary at t00 because the shortest distance to the 40 mm line of TPW about 647 km which might be too far away for the interaction to occur. The rainfall AL pattern of Edouard was not explained by either TPW conditions or shear and motion factors. One possible explanation for this result is that the vertical wind shear changed rapidly between t03 and t00, so that the rainfall pattern might not change along with the shear/motion condition. If the wind shear data at t03 was used for the case of Edouard, the AL pattern was explained. In Western Group, 10 out of 12 cases (83%) of rainfall patterns were explained by TPW distribution and 8 out of 12 cases (67%) were explained by shear and motion vectors (Table 2-10). Thus, in this region, both TPW and vertical wind shear are important for predicting the symmetry of rainfall.

In Central Group, TPW distribution and the distance to TPW contour line of 40mm
suggested that storms should have more S patterns. Wind shear and storm motion conditions suggested that storms should have more AR patterns. The rainfall analysis showed that the AR pattern dominated for 12 out of 17 storms, while 5 storms (Matthew 2004, Arlene 2005, Gustav 2008, Claudette 2009, and Isaac 2012) had the S pattern. As expected, no storms had the AL pattern. Although eight storms eventually completed an ET after landfall, the averaged distance to TPW boundary at t00 for the storms was approximately 505 km and the storms usually completed ET more than 36 hours later from t00. As a result, the storms might be too far away to interact with a frontal boundary at t00, likely explaining why no AL patterns were observed. For the storms that had the AR pattern, the average speed of wind shear was approximately 11 m s\(^{-1}\), which is considered strong (> 5 m s\(^{-1}\)) so that the shear component contributed to the rainfall distribution more than storm motion (Chen et al., 2006). As a result, the rainfall distribution of 11 out of 12 storms was explained by vertical wind shear. The rainfall distribution for the remaining storm (Katrina 2005) was explained by TPW distribution. Among the storms that had the S pattern, the rainfall patterns for 4 storms except Arlene 2005 were explained by either shear/motion component or TPW distribution. However, the case of Arlene was not explained by TPW conditions and the component of shear/motion. One possible explanation is that the 40 mm line of TPW didn’t match with a frontal boundary, so that there could be data errors for TPW conditions. Among all 17 storms, the rainfall pattern for 9 storms (53%) was explained by TPW distribution, and 14 storms (82%) was explained by shear/motion factors. (Table 2-10).

In Eastern Group, it was more complicated to apply the TPW distribution and the wind shear/motion component for the rainfall distribution patterns than for other groups’ cases because many storms completed ET. As a result, only 4 cases (29%) of rainfall
patterns were explained by TPW distribution, and 7 cases (50%) were explained by vertical wind shear and storm motion without considering ET process (Table 2-10). Among all 14 storms, 7 storms (50%) had the AL pattern, and 6 storms (Mitch 1998, Gordon 2000, Gabrielle 2001, Henri 2003, Alberto 2006, and Barry 2007) completed ET from the 7 storms. Except for the case of Gabrielle and Henri, the distances to the 40mm line of TPW for other 4 storms were less 340 km which indicates a likely interaction with a frontal boundary. In the case of Gabrielle, the distance to the 40mm line of TPW was about 365 km which is close to the natural break of 340 km. However, the storm completed an ET after 120 hours from landfall, so that it could possibly indicate not interaction with a front. The surface weather map confirmed that a long cold front was located far away than the distance of 340 km. The factor of shear/motion suggested that the storm should have an AL pattern. In the case of Henri, the distance to TPW was about 622 km, and the storm completed an ET after 81 hours from landfall. However, the rainfall pattern was explained by the component of shear/motion. Debby 2012 produced the AL rainfall pattern, but didn't complete an ET. In the case of Debby, a cold front was located on the left side of storm center within 227 km, transporting a cool air mass near to the storm to produce more rainfall on the left side of the storm.

In Eastern Group, three storms (Irene 1999, Charley 2004, Wilma 2005) had S patterns, and all they completed ET more than 24 hours later (87, 27, and 39 hours) from landfall. In the case of Irene, an AR pattern was suggested based on TPW distribution, and the distance to the 40mm line of TPW line on the left side of storm was about 555 km at t00. However, the shear/motion component explained the S pattern due to the $346^\circ$ of angle difference and approximately 13 m s$^{-1}$ of shear speed. In the case of Charley, the distance to the 40mm line of TPW line on the left side of storm was about
473 km at t00. TPW distributions between on the left and the right side of the storm were not significantly different, explaining the S pattern even though the shear/motion component suggested that the storm should produce an AL pattern. For Wilma 2005, the distance to the 40mm line of TPW line on the left side of the storm was about 364 km at t00 which could be close enough to interact with the frontal boundary, and the position of the TPW line coincided with a cold front from the analysis of a surface weather map. However, the storm completed an ET after 39 hours from the time closest to landfall, so the storm might not interact with the frontal boundary at t00. The rainfall pattern of this storm was caused by shear/motion component of 29° of angle difference and 22 m s⁻¹ of shear speed.

There were 4 storms (Earl 1998, Harvey 1999, Bonnie 2004, and Fay 2008) that had AR patterns in Eastern Group. In the case of Earl, the AR pattern was only explained by the significantly different TPW distribution between on the left and the right side. Although Earl completed an ET after 12 hours from landfall and the distance to the 40mm line of TPW at t00 was about 264 km, the measured distance was caused by the transported dry air mass from a high-pressure system over the Central U.S, resulting in the AR pattern. A cold front was located more than 550 km away from the storm center. In the case of Harvey, the distance to the 40mm of TPW line was 332 km which means that the storm should interact with a frontal boundary. However, a cold front was located farther away than this distance, so that no interaction likely took place. The amount of TPW on the left was significantly less than on the right side of the storm, explaining the AR pattern. For the case of Bonnie, the difference of TPW distribution on both sides of the storm explained the AR pattern. In the case of Fay, the storm completed an ET, but it took 189 hours to experience an ET process after landfall. Also, the distance to the 40
mm line of TPW was about 734 km at t00. The AR pattern was explained by the component of wind shear/storm motion.

Discussion and Limitation

The availability of moisture changes as TCs make landfall over major land masses, and the amount of moisture available is an important factor for rainfall production. This research measured the distribution of volumetric rainfall around TCs at the time closest to landfall and associates its spatial patterns with atmospheric moisture and the combination of vertical wind shear and storm motion. The hypothesis related to moisture was that if less moisture exists on the left (right) side of the storm, then less rainfall would be produced on the left (right) side. Also, the distance to TPW contour line of 40 mm was calculated to determine how close the continental dry air mass or a frontal boundary existed to storms. In addition, the angle difference between the direction of storm motion and vertical wind shear at the time closest to landfall was analyzed to test the hypothesis that more rainfall should occur on the right side of the storm, considering storm’s cyclonic motion. The analysis included the 43 TCs that made landfall over the U.S. Gulf Coast from 1998 to 2015. The cases were divided into 3 groups depending on the landfall location and storm motion direction. A GIS was utilized to perform the spatial analysis of rainfall and TPW, and Mann-Whitney U tests determined whether statistically significant differences existed between the groups in terms of moisture, vertical wind shear, storm motion, and rainfall.

The results of this study support those of previous studies (Chen et al., 2006; Corbosiero and Molinari, 2002, 2003; Hernandez and Matyas, 2016; Jiang et al., 2008b, c; Kimball 2008; Lonfat et al., 2007; Matyas, 2010b) by showing that the storm’s rainfall distribution patterns are influenced by moisture, vertical wind shear, and storm motion.
This research also identified which factors contributed more to the storm’s rainfall distribution regionally. Although TPW conditions and vertical wind shear were the crucial component for the symmetry of storm’s rainfall in general, the storms that made landfall over Texas were influenced by the dry air from the continent to produce less rainfall on the left side of the storm. The rainfall distribution patterns for the storms making landfall over the central Gulf coastal states were mainly determined by the vector of vertical wind shear as moisture was generally plentiful, and had more rainfall on the right side of the storm. In the case of storms making landfall over the Florida peninsula, vertical wind shear was the dominant factor for the symmetry of rainfall distribution. However, the storms tended to interact with a cooler and drier air mass from a frontal boundary to produce more rainfall on the left side of the storm if the moisture boundary existed within approximately 330-340 km of the storm center. This study is the first attempt to measure the distance to TPW boundary from a TC center to explain the distribution patterns of TC rainfall and reveals that moisture conditions are as much important as the component of shear/motion for TC rainfall distribution in the western Gulf states and the Florida peninsula.

There are several limitations of this research. The rainfall patterns were not explained by moisture conditions and combined shear and motion vectors in two cases. One possible explanation is that TC rainfall was only examined at the time closest to landfall so that changes in the spatial patterns were not measured as TCs approached the coastline and moved inland. Future research should analyze the evolution of TC rainfall patterns prior to landfall as TPW conditions change through time, considering a potential time lag between TPW conditions and TC rainfall distribution. Another limitation was that only 40 mm of TPW was considered when determining the location of a non-
tropical air mass, and this contour line didn’t match with the location of an actual cold front in all cases. Therefore, a future research should investigate which values of TPW are the most representative of the location of a frontal boundary in NARR.
Table 2-1. The 12 selected storms (Western Group) that made landfall over from 1998 to 2015. TS: Tropical in Nature, DS: Disturbance, ET: Extra tropical

<table>
<thead>
<tr>
<th>Storms that made landfall over Texas (Western Group)</th>
<th>Year</th>
<th>Time closest to landfall in NARR data</th>
<th>End phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHARLEY</td>
<td>1998</td>
<td>09 UTC 22 Aug</td>
<td>TS</td>
</tr>
<tr>
<td>FRANCES</td>
<td>1998</td>
<td>06 UTC 11 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>BRET</td>
<td>1999</td>
<td>00 UTC 23 Aug</td>
<td>TS</td>
</tr>
<tr>
<td>FAY</td>
<td>2002</td>
<td>09 UTC 07 Sep</td>
<td>DS</td>
</tr>
<tr>
<td>CLAUDETTE</td>
<td>2003</td>
<td>15 UTC 15 Jul</td>
<td>DS</td>
</tr>
<tr>
<td>GRACE</td>
<td>2003</td>
<td>12 UTC 31 Aug</td>
<td>TS</td>
</tr>
<tr>
<td>RITA</td>
<td>2005</td>
<td>09 UTC 24 Sep</td>
<td>DS</td>
</tr>
<tr>
<td>ERIN</td>
<td>2007</td>
<td>12 UTC 16 Aug</td>
<td>DS</td>
</tr>
<tr>
<td>HUMBERTO</td>
<td>2007</td>
<td>06 UTC 13 Sep</td>
<td>DS</td>
</tr>
<tr>
<td>DOLLY</td>
<td>2008</td>
<td>18 UTC 23 Jul</td>
<td>DS</td>
</tr>
<tr>
<td>EDOUARD</td>
<td>2008</td>
<td>12 UTC 05 Aug</td>
<td>DS</td>
</tr>
<tr>
<td>IKE</td>
<td>2008</td>
<td>06 UTC 13 Sep</td>
<td>ET</td>
</tr>
</tbody>
</table>

Table 2-2. The 17 selected storms (Central Group) that made landfall over Louisiana, Mississippi, Alabama, and the western Florida from 1998 to 2015. TS: Tropical in Nature, DS: Disturbance, ET: Extra tropical

<table>
<thead>
<tr>
<th>Storms that made landfall over Louisiana, Mississippi, Alabama, and NW Florida (Central Group)</th>
<th>Year</th>
<th>Time closest to landfall in NARR data</th>
<th>End phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEORGES</td>
<td>1998</td>
<td>12 UTC 28 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>HERMINE</td>
<td>1998</td>
<td>06 UTC 20 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>HELENE</td>
<td>2000</td>
<td>12 UTC 22 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>BARRY</td>
<td>2001</td>
<td>06 UTC 06 Aug</td>
<td>DS</td>
</tr>
<tr>
<td>HANNA</td>
<td>2002</td>
<td>09 UTC 14 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>ISIDORE</td>
<td>2002</td>
<td>06 UTC 26 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>LILI</td>
<td>2002</td>
<td>12 UTC 03 Oct</td>
<td>TS</td>
</tr>
<tr>
<td>BILL</td>
<td>2003</td>
<td>18 UTC 30 Jun</td>
<td>ET</td>
</tr>
<tr>
<td>IVAN</td>
<td>2004</td>
<td>06 UTC 16 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>MATTHEW</td>
<td>2004</td>
<td>12 UTC 10 Oct</td>
<td>ET</td>
</tr>
<tr>
<td>ARLENE</td>
<td>2005</td>
<td>18 UTC 11 Jun</td>
<td>ET</td>
</tr>
<tr>
<td>CINDY</td>
<td>2005</td>
<td>03 UTC 06 Jul</td>
<td>DS</td>
</tr>
<tr>
<td>DENNIS</td>
<td>2005</td>
<td>18 UTC 10 Jul</td>
<td>ET</td>
</tr>
<tr>
<td>KATRINA</td>
<td>2005</td>
<td>12 UTC 29 Aug</td>
<td>ET</td>
</tr>
<tr>
<td>GUSTAV</td>
<td>2008</td>
<td>15 UTC 01 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>CLAUDETTE</td>
<td>2009</td>
<td>06 UTC 17 Aug</td>
<td>TS</td>
</tr>
<tr>
<td>ISAAC</td>
<td>2012</td>
<td>09 UTC 29 Aug</td>
<td>TS</td>
</tr>
</tbody>
</table>
Table 2-3. The 14 selected storms (Eastern Group) that made landfall over Florida Peninsula from 1998 to 2015. TS: Tropical in Nature, DS: Disturbance, ET: Extra tropical

<table>
<thead>
<tr>
<th>Storms that made landfall over Florida Peninsula (Eastern Group)</th>
<th>Year</th>
<th>Time closest to landfall in NARR data</th>
<th>End Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>EARL</td>
<td>1998</td>
<td>06 UTC 03 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>MITCH</td>
<td>1998</td>
<td>12 UTC 05 Nov</td>
<td>ET</td>
</tr>
<tr>
<td>HARVEY</td>
<td>1999</td>
<td>18 UTC 21 Sep</td>
<td>TS</td>
</tr>
<tr>
<td>IRENE</td>
<td>1999</td>
<td>21 UTC 15 Oct</td>
<td>ET</td>
</tr>
<tr>
<td>GORDON</td>
<td>2000</td>
<td>03 UTC 18 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>GABRIELLE</td>
<td>2001</td>
<td>12 UTC 14 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>HENRI</td>
<td>2003</td>
<td>09 UTC 05 Sep</td>
<td>ET</td>
</tr>
<tr>
<td>BONNIE</td>
<td>2004</td>
<td>15 UTC 12 Aug</td>
<td>DS</td>
</tr>
<tr>
<td>CHARLEY</td>
<td>2004</td>
<td>21 UTC 13 Aug</td>
<td>ET</td>
</tr>
<tr>
<td>WILMA</td>
<td>2005</td>
<td>09 UTC 24 Oct</td>
<td>ET</td>
</tr>
<tr>
<td>ALBERTO</td>
<td>2006</td>
<td>18 UTC 13 Jun</td>
<td>ET</td>
</tr>
<tr>
<td>BARRY</td>
<td>2007</td>
<td>15 UTC 02 Jun</td>
<td>ET</td>
</tr>
<tr>
<td>FAY</td>
<td>2008</td>
<td>09 UTC 19 Aug</td>
<td>ET</td>
</tr>
<tr>
<td>DEBBY</td>
<td>2012</td>
<td>21 UTC 26 Jun</td>
<td>TS</td>
</tr>
</tbody>
</table>
Table 2-4. The Mann-Whitney \( U \) Test results (\( p \)-values) of the averaged total TPW during 24 hours (\( \alpha = 0.05 \)).

<table>
<thead>
<tr>
<th>Data</th>
<th>Western vs Central</th>
<th>Western vs Eastern</th>
<th>Central vs Eastern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total TPW t24</td>
<td>0.035*</td>
<td>0.860</td>
<td>0.021*</td>
</tr>
<tr>
<td>Total TPW t21</td>
<td>0.004*</td>
<td>0.432</td>
<td>0.006*</td>
</tr>
<tr>
<td>Total TPW t18</td>
<td>0.004*</td>
<td>0.732</td>
<td>0.005*</td>
</tr>
<tr>
<td>Total TPW t15</td>
<td>0.006*</td>
<td>0.403</td>
<td>0.005*</td>
</tr>
<tr>
<td>Total TPW t12</td>
<td>0.004*</td>
<td>0.595</td>
<td>0.001*</td>
</tr>
<tr>
<td>Total TPW t09</td>
<td>0.002*</td>
<td>0.462</td>
<td>0.003*</td>
</tr>
<tr>
<td>Total TPW t06</td>
<td>0.002*</td>
<td>0.631</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Total TPW t03</td>
<td>0.002*</td>
<td>0.297</td>
<td>0.007*</td>
</tr>
<tr>
<td>Total TPW t00</td>
<td>0.003*</td>
<td>0.560</td>
<td>0.003*</td>
</tr>
</tbody>
</table>

* The \( p \)-value less than 0.05; the median of TPW values between two groups are significantly different.

Table 2-5. The Mann-Whitney \( U \) Test results (\( p \)-values) of the averaged total TPW on the left side of the storm (Cells 1, 4, 7) during 24 hours (\( \alpha = 0.05 \)).

<table>
<thead>
<tr>
<th>Data</th>
<th>Western vs Central</th>
<th>Western vs Eastern</th>
<th>Central vs Eastern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left TPW t24</td>
<td>0.001*</td>
<td>0.820</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Left TPW t21</td>
<td>&lt; 0.001*</td>
<td>0.631</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Left TPW t18</td>
<td>&lt; 0.001*</td>
<td>0.781</td>
<td>0.001*</td>
</tr>
<tr>
<td>Left TPW t15</td>
<td>0.001*</td>
<td>0.494</td>
<td>0.009*</td>
</tr>
<tr>
<td>Left TPW t12</td>
<td>0.002*</td>
<td>0.899</td>
<td>0.017*</td>
</tr>
<tr>
<td>Left TPW t09</td>
<td>&lt; 0.001*</td>
<td>0.899</td>
<td>0.005*</td>
</tr>
<tr>
<td>Left TPW t06</td>
<td>0.001*</td>
<td>0.820</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Left TPW t03</td>
<td>0.002*</td>
<td>0.631</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Left TPW t00</td>
<td>0.016*</td>
<td>0.118</td>
<td>0.001*</td>
</tr>
</tbody>
</table>

* The \( p \)-value less than 0.05; the median of TPW values between two groups are significantly different.
Table 2-6. The Mann-Whitney U Test results (p-values) of the averaged total TPW on the right side of the storm (Cells 3, 6, 9) during 24 hours (α = 0.05).

<table>
<thead>
<tr>
<th>Data</th>
<th>Western vs Central</th>
<th>Western vs Eastern</th>
<th>Central vs Eastern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right TPW t24</td>
<td>1.000</td>
<td>0.969</td>
<td>0.868</td>
</tr>
<tr>
<td>Right TPW t21</td>
<td>0.325</td>
<td>0.742</td>
<td>0.399</td>
</tr>
<tr>
<td>Right TPW t18</td>
<td>0.656</td>
<td>0.705</td>
<td>0.710</td>
</tr>
<tr>
<td>Right TPW t15</td>
<td>0.471</td>
<td>0.940</td>
<td>0.518</td>
</tr>
<tr>
<td>Right TPW t12</td>
<td>0.647</td>
<td>0.870</td>
<td>0.681</td>
</tr>
<tr>
<td>Right TPW t09</td>
<td>0.283</td>
<td>0.382</td>
<td>0.830</td>
</tr>
<tr>
<td>Right TPW t06</td>
<td>0.245</td>
<td>0.231</td>
<td>0.984</td>
</tr>
<tr>
<td>Right TPW t03</td>
<td>0.140</td>
<td>0.041*</td>
<td>0.710</td>
</tr>
<tr>
<td>Right TPW t00</td>
<td>0.043*</td>
<td>0.004*</td>
<td>0.830</td>
</tr>
</tbody>
</table>

* The p-value less than 0.05; the median of TPW values between two groups are significantly different.

Table 2-7. The Mann-Whitney U Test results (p-values) of the averaged TPW on the left side (Cells 1, 4, 7) versus on the right side (Cells 3, 6, 9) of the storm during 24 hours (α = 0.05).

<table>
<thead>
<tr>
<th>Data</th>
<th>Western Group</th>
<th>Central Group</th>
<th>Eastern Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPW left vs right t24</td>
<td>0.001*</td>
<td>0.518</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t21</td>
<td>&lt; 0.001*</td>
<td>0.205</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t18</td>
<td>&lt; 0.001*</td>
<td>0.114</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t15</td>
<td>0.001*</td>
<td>0.073</td>
<td>0.001*</td>
</tr>
<tr>
<td>TPW left vs right t12</td>
<td>&lt; 0.001*</td>
<td>0.057</td>
<td>0.001*</td>
</tr>
<tr>
<td>TPW left vs right t9</td>
<td>&lt; 0.001*</td>
<td>0.053</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t6</td>
<td>&lt; 0.001*</td>
<td>0.029*</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t3</td>
<td>0.003*</td>
<td>0.008*</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>TPW left vs right t0</td>
<td>0.005*</td>
<td>0.006*</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

* The p-value less than 0.05; the median of TPW values between two groups are significantly different.
Table 2-8. The Mann-Whitney U Test results (p-values) of the angle difference between vertical wind shear and storm motion at t00 by groups. (α = 0.05).

<table>
<thead>
<tr>
<th></th>
<th>Western Group</th>
<th>Central Group</th>
<th>Eastern Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>0.454</td>
</tr>
</tbody>
</table>

* The p-value less than 0.05; the median of TPW values between two groups are significantly different.

Table 2-9. The Mann-Whitney U Test results (p-values) of the storm total volumetric rain over the entire outlined area between the left and the right side of the storm at t00 by groups (α = 0.05).

<table>
<thead>
<tr>
<th></th>
<th>Western Group Left vs Right</th>
<th>Central Group Left vs Right</th>
<th>Eastern Group Left vs Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.012*</td>
<td>0.005*</td>
<td>0.595</td>
</tr>
</tbody>
</table>

* The p-value less than 0.05; the median of TPW values between two groups are significantly different.

Table 2-10. The percentage of storms’ rainfall patterns that can be explained by TPW distribution or vertical wind shear and storm motion without considering ET process.

<table>
<thead>
<tr>
<th></th>
<th>TPW Conditions</th>
<th>Vertical Wind Shear / Storm Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Group</td>
<td>10/12 (83%)</td>
<td>8/12 (67%)</td>
</tr>
<tr>
<td>Central Group</td>
<td>9/17 (53%)</td>
<td>14/17 (82%)</td>
</tr>
<tr>
<td>Eastern Group</td>
<td>4/14 (29%)</td>
<td>7/14 (50%)</td>
</tr>
</tbody>
</table>
Figure 2-1. Three regional groups with selected storm tracks every 3 hours from 24 hours prior to landfall to the time closest to landfall
Figure 2-2. The amount of TPW at 00 UTC 29 August 2005 during the landfall of Hurricane Katrina. Nine cells comprise the grid (orange) centered on the TC position and oriented according to storm forward motion. The yellow dashed line represents a diameter for the region within which a TC obtains its moisture according to Trenberth et al., (2003). TPW on the left side of a storm (Cell 1, 4 & 7) and on the right side of a storm (Cell 3, 6 & 9) are measured separately. The shortest distance to TPW contour line of 40mm (red) from a storm center is measured.
Figure 2-3. Regions where the rain rate exceeds of 5 mm hr\(^{-1}\) were selected for analysis (red line). Then, the rain-field areas that intersected with or were within 250km of the storm center (black line) were selected for analysis.
Figure 2-4. The symmetry of TC rainfall distribution. (a) Asymmetrical rainfall distribution pattern with more rain rate on the right side (AR) demonstrated at the time of landfall with Charley 1998. (b) Symmetrical rainfall distribution pattern (S) demonstrated at the time closest to landfall with Matthew 2004. (c) Asymmetrical rainfall distribution pattern with more rain rate on the left side (AL) demonstrated at the time closest to landfall with Gabrielle 2001.
Figure 2-5. The boxplots for the averaged total TPW in the grid boxes surrounding storms by regional groups during 24 hours.
Figure 2-6. The boxplots for the averaged total TPW on the left side (Cells 1, 4, 7) of storm by regional groups during 24 hours.
Figure 2-7. The boxplots for the averaged total TPW on the right side (Cells 3, 6, 9) of storm by regional groups during 24 hours.
Figure 2-8. The 40mm line of TPW boundary at t00 (a red line). (a) 1998 Charley from Western Group, (b) 2004 Ivan from Central Group, (c) 1998 Mitch from Eastern Group
Figure 2-9. The boxplots for the averaged shortest distance between the storm centers and TPW contour line of 40 mm by regional groups during 24 hours.

Figure 2-10. The boxplots for the distance to TPW contour line of 40 mm at t00 by the rainfall distribution pattern. The X demarcates the mean value.
Figure 2-11. The averaged storm motion vector and the averaged vertical wind shear vector in quadrants by regional groups (a: Western Group, b: Central Group, c: Eastern Group). A shaded region is where rainfall should occur according to the combined vectors and storm’s counterclockwise rotation.
Figure 2-12. The boxplots for the total volumetric rainfall over the entire outlined area at t00 by groups. The X demarcates the mean value.

Figure 2-13. The boxplots for the volumetric rainfall over the entire outlined area between the left and the right side of storm at t00 by groups (km$^3$ hr$^{-1}$).
Figure 2-14. The number of cases exhibiting each rainfall distribution pattern by group.
Corene Matyas is a representative Geographer who studies TCs. Her research philosophy and effort to blend between Geography and Meteorology has shown a different way to conduct TC research from a different perspective. She and her research group have investigated TC precipitation patterns spatially and climatologically. She has mainly utilized a GIS to analyze TC precipitation patterns by measuring the shape of TC rain fields (Matyas 2007, 2008), examining TC rainfall patterns specific to Florida (Matyas 2006, Matyas and Cartaya 2009, Matyas 2014), or examining conditions related to TC rain field size (Matyas 2010b, 2013, 2014). In addition, she guided her research group to investigate TC rainfall patterns over Puerto Rico (Hernandez and Matyas 2016) and the U.S. (Zhou and Matyas 2017) and the evolution of TC precipitation pattern by using shape metrics (Matyas 2007, 2008, Zick and Matyas 2016). As Geographers specialize in the examination of spatial patterns, my current research developed a new approach to examine rainfall asymmetry that compliments the work published by Dr. Matyas and her students.

Previous researchers have found that TC rainfall patterns are influenced by moisture conditions surrounding the TCs. For an example, Kimball’s (2008) modeling study revealed that a dry air intrusion on the left side of the storm from the land caused increased stability on the left side and increased instability on the right side as the dry air circulates counterclockwise from the boundary layer, resulting in lower (higher) rainfall rates on the left (right) side of the storm. However, the current observational study focuses more on the moisture conditions present in the entire atmospheric column by utilizing the value of TPW and determining how it varies in the environment surrounding TCs as they approach landfall. The goal of this research is to investigate the symmetry of
the rainfall distribution pattern for TCs making landfall over the Gulf coastal states and 
associate these patterns with the spatial distribution of atmospheric moisture as 
measured using a GIS. In addition, vertical wind shear and storm motion which are crucial 
factors that influence TC rainfall patterns and have been extensively examined by other 
researchers are also analyzed along with the moisture conditions.

The 43 storms are selected from 1998 to 2015 and they are divided into 3 groups 
depending on the landfall location and storm motion. The TPW data are obtained from 
NARR. The TPW distribution surrounding TCs is measured for the 24-hour time period 
before the time closest to landfall. To measure TPW, a grid box containing 9 cells is 
positioned at the storm center and both sides of each cell are 500 km in length. Also, the 
shortest distance between the storm center and TPW contour line of 40 mm is measured 
to investigate if dry air from the continental air mass is close to the storms or storms 
interact with a frontal boundary. The vector of vertical wind shear from SHIPS data is 
compared to the vector of storm motion at the time closest to landfall. Finally, the 
volumetric rainfall distribution is examined at the time closest to landfall for each storm 
and it is determined whether it is symmetrical or asymmetrical regards to the right and left 
side of the storm. The data for TC rainfall are obtained from TRMM. The rainfall 
distribution patterns are compared with TPW conditions, vertical wind shear and storm 
motion components.

This research shows that TC rainfall distribution patterns are different regionally 
and moisture conditions such as dry air mass from the continent or cooler and drier air 
mass from the mid-latitude weather system are important for TC rainfall distribution along 
with vertical wind shear and storm motion. In addition, the influence of moisture, shear 
and motion factors vary regionally. The storms that made landfall over Texas generally
produced more rainfall on the right side of the storm and the rainfall distribution was
mainly impacted by the proximity of the dry continental air mass west of the storm. Storms
made landfall over the central Gulf coastal states generally produced more rainfall on the
right side of the storm. This study shows that the rainfall pattern in this region was
generally determined by vertical wind shear as ample moisture was present within
approximately 585 km of the storm center. The storms that traveled over the Florida
peninsula generally produced more rainfall on the left side of the storm. This pattern was
associated not only with the vectors of vertical wind shear and storm motion but also
interaction with a frontal boundary. When a frontal boundary existed within approximately
330-340 km of a storm center, the interaction between cooler air from a frontal boundary
and warm/moist air from a TC occurred, resulting in more rainfall on the left side of the
storm.

This study contributes to the literature by suggesting that TC rainfall patterns vary
regionally in the Gulf states and the main environmental conditions that influence on TC
rainfall are also different depending on where the storm is located. Also, this study
suggests that the distance of 330-340 km between a storm center and TPW line of 40 mm
can be a key threshold for interaction between the tropical and continental air masses for
the first time.

However, there are some limitations in this research. In particular, TPW values of
40 mm didn’t coincide with the actual location of a cold front that interacted with a storm
in 3 out of 14 cases in Eastern Group. As a result, it is suggested for the future research
to investigate determine the values of TPW that more accurately indicate the location of
a frontal boundary. One possible reason for the mismatch between TPW values and a
frontal boundary is that a front is a surface feature, but TPW is measured from the entire
column of the atmosphere. As a result, temperature and moisture near the surface
should be analyzed in conjunction with TPW to better define the location of a frontal
boundary when examining TCs that interact with the middle latitude westerlies.
Therefore, future research should examine in more detail how the availability of moisture
changes as TCs approach land and quantify which values of TPW are most
representative of moisture boundaries that can enhance rainfall production.
LIST OF REFERENCES


Matyas, C. J. 2013: Processes influencing rain-field growth and decay after tropical cyclone landfall in the United States. *Journal of Applied Meteorology and Climatology, 52*, 1085–1096. DOI: 10.1175/JAMC-D-12-0153.1


NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/


Zagrodnik, J. P., and H. Jiang, 2013: Investigation of PR and TMI version 6 and version 7 rainfall algorithms in landfalling tropical cyclones relative to the NEXRAD stage-IV multisensor precipitation estimate dataset. *Journal of Applied Meteorology and Climatology*, **52**: 2809-2827. DOI: 10.1175/JAMC-D-12-0274.1


BIOGRAPHICAL SKETCH

Mr. Sanghoon Kim is from Seoul, South Korea. He studied meteorology for his bachelor’s degree from Northern Illinois University. He received his Master of Science degree from the Department of Geography at the University of Florida in the summer of 2017. He is interested in spatial analysis, climate, hurricanes and natural hazards.