2009

Atlantic tropical cyclone: climatology and the contribution to monthly and seasonal rainfall in the eastern U.S. 1960-2007

Ricardo Chabarria Nogueira
Louisiana State University and Agricultural and Mechanical College, ricnogue@yahaoo.com

Recommended Citation

Nogueira, Ricardo Chabarria, "Atlantic tropical cyclone: climatology and the contribution to monthly and seasonal rainfall in the eastern U.S. 1960-2007" (2009). *LSU Doctoral Dissertations*. 3311.
https://digitalcommons.lsu.edu/gradschool_dissertations/3311

ATLANTIC TROPICAL CYCLONE: CLIMATOLOGY AND THE CONTRIBUTION TO MONTHLY AND SEASONAL RAINFALL IN THE EASTERN U.S. 1960-2007

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

In

The Department of Geography and Anthropology

By
Ricardo Chabarria Nogueira
B.A., Federal University of Pelotas, Brazil, 1982
M.S., Western Michigan University, 2005
May 2009

ACKNOWLEDGMENTS

This dissertation was made possible through the help, advice and support of many individuals. I would like to extend my profound thanks to my academic advisor, Dr. Barry Keim, for his guidance, suggestions, enthusiasm, and friendship offered during the many phases of this investigation. I also wish to thank the other members of my dissertation committee, Dr. David Brown, Dr. John Pine, Dr. S. A, Hsu and Dr. Gary Breitenbeck for their interest, insightful suggestions and advice. Their contribution added immensely to this research. I am also grateful to Dr. Kevin Robbins, Director of the Southern Regional Climate Center, for all the assistance provided and for continual financial support. Special thanks are extended to the Department of Geography and Anthropology of their support and for funding my research.

A very special thanks goes to Dr. Elen Cutrim for her help, but also for her friendship, her enthusiasm and example as a human being is contagious. I would like to thank Andrew Augustine for his help and his friendship. In addition, I extend a special thanks to Dana Sanders for always being helpful.

I also thank all my friends of The Boarder and Tango Lagniappe, and to my family for their constant support and encouragement.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

LIST OF TABLES v

LIST OF FIGURES vi

ABSTRACT ix

I INTRODUCTION 1

II CONTRIBUTIONS OF ATLANTIC TROPICAL CYCLONES TO MONTHLY AND SEASONAL RAINFALL IN THE EASTERN UNITED STATES -1960-2007 5
- INTRODUCTION 5
- TC RAINFALL DISTRIBUTION 6
- STATEMENT OF PROBLEM 6
- DATA AND METHODS 7
- RESULTS 11
  - Tropical Cyclones Affecting the United States 11
  - Storm Day 12
  - Storm Track Density 12
  - Percentage of Tropical Rainfall Contribution 17
  - TC Seasonal Rainfall Distribution 24
  - TC Rainfall Contribution Comparison 24
  - Seasonal 26
- SUMMARY AND DISCUSSION 26

III CHARACTERISTICS OF TROPICAL CYCLONE RAINFALL OVER THE EASTERN UNITED STATES 31
- INTRODUCTION 31
- DATA 32
- METHODS 34
  - Non-parametric Correlations 36
  - Teleconnections 37
- RESULTS AND DISCUSSION 38
  - El Niño Southern Oscillation (ENSO) 43
  - Atlantic Multidecadal Oscillation – AMO 43
- SUMMARY 48

IV VARIABILITY OF RAINFALL FROM TROPICAL CYCLONE IN EAST UNITED STATES AND ITS RELATION WITH AMO AND ENSO 50
- INTRODUCTION 50
- DATA 53
- METHODS 54
- RESULTS AND DISCUSSION 55

Storm Days 55
Spatial and Temporal Variation of Major Storms 60
TC Rainfall Trend 64
TC Rainfall and Teleconnections 65
SUMMARY 66

V CONCLUDING REMARKS 74
DATA AND METHODS 74
Objective One 75
Objective Two 76
Objective Three 77
SIGNIFICANCE OF FINDINGS 79
FUTURE WORK 79

BIBLIOGRAPHY 81

VITA 89

LIST OF TABLES

TABLE 1: FREQUENCY OF HURRICANES AND TROPICAL STORMS............................ 14

TABLE 2: *T-TEST* SPSS OUTPUT COMPARING ALL VARIABLES WITH ENSO............. 46

TABLE 3: *T-TEST* COMPARING ALL VARIABLES WITH AMO (+) WITH AMO (-) 47

TABLE 4: KENDALL’S TAU B TEST OF CORRELATION RESULTSL. 49

TABLE 5: SAFFIR-SIMPSON HURRICANE SCALE (SSHS) 52

LIST OF FIGURES

FIGURE 1 : (A) HURRICANE CAMILLE TRACK (SOLID LINE) WITH THE 500 KM BUFFER (SHADOW AREA). DARK DOTS REPRESENT THE STATIONS UNDER THE TC RAIN BUFFER, AND THE LIGHT DOTS REPRESENT STATIONS IN THE STUDY NOT AFFECTED BY CAMILLE; (B) BUFFER OF ALL STORM 500 KM FROM 1960-2007 (RED AREA). DARK DOTS REPRESENT THE 717 STATIONS INCLUDED IN THIS STUDY. 11

FIGURE 2: ANNUAL NUMBER OF NAMED TROPICAL STORMS OVER THE ATLANTIC BASIN FOR THE PERIOD OF RELIABLE RECORD FROM 1960 TO 2007. THE FIVE-YEAR RUNNING MEAN (SOLID LINE) IS SUPERIMPOSED ON THE TIME SERIES. 13

FIGURE 3: ANNUAL NUMBER OF STORMS WITHIN 500 KM FROM THE U.S. COAST FROM 1960 TO 2007.THE 5-YEAR RUNNING MEAN (SOLID LINE) IS SUPERIMPOSED ON THE TIME SERIES. 13

FIGURE 4: STORM DAYS FROM 1960 TO 2007 AND 5- YEAR MOVING AVERAGE (BOLD LINE) 14

FIGURE 5: MONTHLY PERCENTAGE OF STORMS DAYS FROM 1960-2007 15

FIGURE 6: STORM TRACK DENSITY WAS CALCULATED FOR A CELL SIZE OF 0.2° X 0.2° LATITUDE/LONGITUDE, AND SHOWS THE DENSITY OF LINEAR FEATURES IN THE NEIGHBORHOOD OF EACH OUTPUT RASTER CELL. EACH MONTH DURING THE ATLANTIC HURRICANE SEASON (JUNE TO NOVEMBER) IS DISPLAYED FOR TWO STUDY PERIODS. THE LEFT COLUMN DISPLAYS TDS DURING CRY’S (1967)1931-1960 STUDY PERIOD. THE SHADED BLUE REGIONS REPRESENT THE HIGHEST LINE DENSITY. THE RIGHT COLUMN REPRESENTS THE TDS DURING 1960-2007 STUDY PERIOD. SHADED RED REGIONS REPRESENT THE HIGHEST LINE DENSITY 18

FIGURE 7: JUNE TO AUGUST MONTHLY RAINFALL AVERAGE AND TC MONTHLY RAINFALL AVERAGE FROM 1960-2007. EACH MONTH SHOWS THE STORM BUFFER REGION (LIGHT BLUE LINE). LEFT COLUMN REPRESENTS THE SEASONAL RAINFALL AVERAGE AND THE RIGHT COLUMN THE TC SEASONAL RAINFALL AVERAGE. 20

FIGURE 8: SEPTEMBER TO NOVEMBER MONTHLY RAINFALL AVERAGE AND TC MONTHLY RAINFALL AVERAGE FROM 1960-2007. EACH MONTH SHOWS THE STORM BUFFER REGION (LIGHT BLUE LINE). LEFT COLUMN REPRESENTS THE SEASONAL RAINFALL AVERAGE AND THE RIGHT COLUMN THE TC SEASONAL RAINFALL AVERAGE. 23

FIGURE 9: JUNE TO NOVEMBER MONTHLY TC RAINFALL PERCENTAGE FROM 1960-2007. 28

FIGURE 10: TOTAL RAINFALL JUNE-NOVEMBER (A) AND NON-TROPICAL (B), FROM 1960-2007 29

FIGURE 11: ANNUAL TC RAINFALL AVERAGE (A) AND ANNUAL AVERAGE PERCENTAGE (B), FROM 1960-2007 29

FIGURE 12 : TROPICAL CYCLONE RAINFALL AVERAGE CONTRIBUTION FROM 1931-1960 BY CRY (1967). FIGURES A, B, AND C REPRESENTS THE MONTHS AUGUST, SEPTEMBER, AND AUGUST. FIGURE D REPRESENTS THE SEASONAL TC RAINFALL AVERAGE CONTRIBUTION (JUNE TO OCTOBER). 30

FIGURE 13: STUDY REGION AND U.S. HCN STATIONS. 33

FIGURE 14: PACIFIC NINO 3-4 REGION SST ANOMALIES AND THE JMA ENSO PHASES (RED FOR POSITIVE; WHITE FOR NEGATIVE; AND BLACK FOR NEUTRAL, BASED ON 0.3°C THRESHOLDS. 34

FIGURE 15: NUMBER OF TC AFFECTED STATIONS BY YEAR IN THE EASTERN UNITED STATES. A) TOTAL NUMBER OF AFFECTED STATIONS (BARS), 48-YEAR AVERAGE (DASHED LINE), AND 5-YEAR MOVING AVERAGE (BOLD LINE); B) TOTAL NUMBER OF AFFECTED STATIONS AVERAGED BY THE NUMBER OF STORMS PER YEAR (BARS), 48-YEAR AVERAGE (DASHED LINE), AND THE 5-YEAR MOVING AVERAGE (BOLD LINE). 40

FIGURE 16: (A) ANNUAL AVERAGE OF TC RAINFALL, AND (B) TC RAINFALL CONTRIBUTION IN PERCENTAGE FROM JUNE UNTIL NOVEMBER TOTAL RAINFALL (1960-2007). 41

FIGURE 17: TIME SERIES OF SEASONAL (JUNE TO NOVEMBER) RAINFALL FROM 1960-2007, AND AMO PHASES (DASHED LINES); (A) TOTAL RAINFALL AND TOTAL 5-YEAR RAINFALL MOVING AVERAGE (LINE); (B) TOTAL RAINFALL ANOMALIES FROM AVERAGE (BARS) (AVERAGE=40257 CM, SD= 3779CM); (C) TC RAINFALL ACCUMULATED BY YEAR (BARS) AND 5-YEAR MOVING AVERAGE (LINE); (D) TC RAINFALL ANOMALY ACCUMULATED BY YEAR (AVERAGE= 1931 CM, SD=1731 CM); (E) TC RAINFALL PERCENTAGE OF THE TOTAL RAINFALL (BARS), AND 5-YEAR MOVING AVERAGE (LINE). 44

FIGURE 18: VOLUME AND AREA OF TC RAINFALL FROM 1960-2007. (A) TC RAINFALL VOLUME (BARS), AND TOTAL 5-YEAR RAINFALL MOVING AVERAGE (BOLD LINE) (AVERAGE=103 KM^3, SD= 89 KM^3). (B) TC RAINFALL VOLUME (BARS). (C) AREA OF TC RAINFALL ANOMALY ACCUMULATED BY YEAR AND 5-YEAR MOVING AVERAGE (AVERAGE= 10^6 KM^2, SD=4.4 X10^5 KM^2). (D) AREA OF TC RAINFALL ANOMALIES ACCUMULATED BY YEAR. 45

FIGURE 19 : LEADING CAUSES OF TC DEATHS IN THE U.S. 1979-1999. SOURCE NHC, 2007. 51

FIGURE 20 : BUFFER OF ALL STORM 500 KM FROM 1960-2007 (RED AREA). DARK DOTS REPRESENT THE 717 STATIONS INCLUDED IN THIS STUDY. 54

FIGURE 21: HURRICANE CAMILLE TRACK (SOLID LINE) WITH THE 500 KM BUFFER (SHADOW AREA). DARK DOTS REPRESENT THE STATIONS UNDER THE TC RAIN SHADOW, AND THE LIGHT DOTS REPRESENT STATIONS IN THE STUDY NOT AFFECTED BY CAMILLE. 56

FIGURE 22: STORM DAYS FROM 1931 TO 2007, 5-YEAR MOVING AVERAGE (BOLD LINE), AND DASHED LINE MARKING THE YEAR OF 1960, THAT REPRESENTS THE END OF CRY (1967) STUDY PERIOD. 58

FIGURE 23: MONTHLY STORMS DAYS FROM 1931-1960 AND 1961-2007. 58

FIGURE 24: SD ANOMALIES FROM 1931-2007 (BLUE BARS POSITIVE VALUES, AND WITH BARS NEGATIVE VALUES), AMO 10-YEAR MOVING AVERAGE (LINE), AND ENSO (+) PHASE (RED BARS). THE DARK RED BARS REPRESENT THE STRONGEST ENSO (+) EVENTS. 59

FIGURE 25: STORM DAYS (SDS) ACCUMULATED DAILY, (A) 1931-1960; (B) FROM 1961-2007DURING THE STORM SEASON (JUNE –NOVEMBER). 62

FIGURE 26: NORMALIZED SDS DIFFERENCE BETWEEN 1931-1960 AND 1961-2007 PERIODS (AVERAGE FROM 1931-1960 MINUS AVERAGE FROM 1961-2007). 63

FIGURE 27: MAJOR STORM FREQUENCIES SPATIAL DISTRIBUTION FROM JUNE TO NOVEMBER DURING THE STUDY PERIOD OF 1960-2007. 67

FIGURE 28: SEASONAL FREQUENCY OF MAJOR STORMS (1960 TO 2007) BY WEATHER STATIONS. 71

FIGURE 29: SPATIAL DISTRIBUTION OF THE MAJOR STORMS ANOMALIES DURING THE PERIOD OF 1960 TO 2007. THE RED REGION REPRESENTS THE AREA WITH THE HIGHEST FREQUENCY OF MS COMPARED WITH 71

FIGURE 30**:** YEARLY CHANGE IN TC RAINFALL AT EACH STATION FROM 1960-2007. RED TRIANGLE REPRESENTS STATIONS WHERE THE TREND IS POSITIVE AND SIGNIFICANT AT A=0.05. BLUE CIRCLES INDICATE STATIONS WITH A DECREASE IN TC RAINFALL SIGNIFICANT AT A=0.05. DOTTED POINTS REPRESENT STATIONS WITH NO SIGNIFICANT TREND. 72

FIGURE 31: CORRELATION (95% OF CONFIDENT LEVEL) BETWEEN TC RAINFALL AND AMO. RED CIRCLES REPRESENT A POSITIVE CORRELATION WITH AMO BLUE CIRCLES NEGATIVE CORRELATION WITH AMO. 72

FIGURE 32: CORRELATION (95% OF CONFIDENCE LEVEL) BETWEEN TC RAINFALL AND NIÑO 3.4 ANNUAL AVERAGE. RED CIRCLES REPRESENTS NEGATIVE CORRELATION AT A=0.05. 73

ABSTRACT

Tropical cyclones (TCs) are among the most devastating of natural disasters, producing high winds, heavy rainfall, and floods. When TC remnants are considered, these events have impacts nearly nationwide across the U.S. Tropical cyclone activity in the North Atlantic Basin experiences great variability on intra-annual, interannual, and interdecadal timescales. That variability is often associated with El Niño Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO).

George Cry (1967), in his pioneering study of tropical cyclone-induced rainfall found that TC rainfall presents an intraseasonal pattern over the eastern Unite States, contributing up to 40% of the monthly rainfall. This study replicates much of what was done by Cry (1967) using a denser raingage network and more sophisticated techniques for analysis. Rainfall data for this study comes from 717 stations from the Historical Climate Network covering 31 states to capture the TC contribution in the monthly and seasonal precipitation in the Eastern United States.

An approach was used to separate TC rainfall from non-tropical rainfall from 1960-2007. Results showed that September has the highest TC rainfall contribution. Coastal regions of North Carolina, Virginia, and Alabama receive more than 30% of monthly rainfall totals from TCs. Comparisons between 1931-1960 and 1960-2007 shows that the storm track density shifted slightly eastward.

TC rainfall, during the period 1960-2007, presented great interannual variability in the frequency, intensity, and duration of the storms (number of storm days). ENSO and AMO phases were found to play different roles in relation to TC rainfall contribution in the U.S. ENSO has a significant signal in relation to the number of storms, but did not have a statistically significant signal in the total of TC rainfall in the eastern U.S. AMO showed

a positive correlation with individual stations in the Gulf Coast and in Maine. In addition, ENSO phases are correlated with TC rainfall in Texas.

I INTRODUCTION

Tropical Cyclones (TC) are one of the most powerful features in nature and can produce catastrophic social, economic and ecological impacts. This fact, combined with the United States coastline becoming increasingly more susceptible to TC damages, has led to catastrophic losses in the U.S. (Blake, et al., 2007). The susceptibly is due to increasing population in the last four decades, beach erosion, and coastal subsidence (Blake, Rappaport and Landsea 2007). TCs can produce rain from a light drizzle to an extreme flood in a short period, and in a single location could represent up to 50% to 100% of mean annual precipitation in only a few days (Glenson 2006, Simpson and Riehl 1981). Rainfall produced by tropical storms can extend for hundreds of kilometers from their centers causing property damage, flooding, and mudslides in some regions, but the same rain can be beneficial to regions experiencing drought (Larson, Zhou and Higgins 2005). TC intensity is not the principal element affecting of the amount of rainfall, storms with a slow forward velocity have a tendency to produce large quantities of rainfall at a given location as well (Emanuel 2005)**.**

Tropical cyclone activity in the North Atlantic Basin experiences great variability on intra-annual, the interannual (El Nino-Southern Oscillation), and the interdecadal (Atlantic Sea Surface Temperature - SST) timescales (Keim and Robbins 2006, Landsea, et al. 1999, Gray 2006). TC seasonality is associated with the annual cycle of SST, with peak in late summer and early fall. Some active years with 15 or more named tropical storms include -2005 (27), 2003(16), 2001(15), 1995(19), and 1969 (17). However, there are also relatively inactive years with eight storms or less – 1997, 1994, etc. Many studies have identified an empirical relationship between SST and TC activity where warmer SSTs enhance development of TC (Shapiro and Goldenberg, 1998, and

Molinari and Mestas-Nuñez, 2003). Other studies investigated potential effects of long-term global warming on Atlantic SST and its correlation with the number and strength of TC. However, Goldenberg et al. (2001) pointed out that those studies were inconclusive and explained that the multidecadal-scale variability of TC is greater than the possible small increase in SST caused by global warming. Landsea et al. (1999) point out that the discrepancy between interannual and interdecadal TC activity with the SST in the North Atlantic Basin may be explained by the interactions of the SSTs with other environmental controls such as El Niño-Southern Oscillation (ENSO). For example, El Niño reduces TC activity through anomalous increase in upper tropospheric westerly winds over the Caribbean basin and the equatorial Atlantic (Gray, 1984). Another important component potentially related to hurricane activity is climate change.

Global warming is among the most controversial scientific topics today. The concentration of greenhouse gases such as carbon dioxide (CO_2), methane, and others, have increased over the past century due the anthropogenic sources. Many studies argue that higher levels of greenhouse gases have increased the number of extreme weather events and have changed earth's climate (Emanuel, 2005). Global Circulation Models (GCMs), working with a doubling of CO_2 over the next 50 years, forecast an increase in the global sea surface temperature (SST) (Anthes et al., 2006). The models show a 20% increase in precipitation because of warmer sea surface temperature (SST), perhaps related to tropical activity (Knutson et al., 2001). However, some scientists are unconvinced that all recent climate change has resulted from anthropogenic effects. They even suggest that the observed climate change might be the result of natural causes (Landsea et al., 1999, Pielke et al., 2005, Grey, 2006). TCs play an important role in the U.S. climate. Keim (1999) noted that most of the 25 greatest storms recorded in the southern U.S. were related with TC. In addition, Karl et al. (2005) confirmed that TCs show a great contribution in the annual precipitation in southeast costal zone.

Henderson-Sellers et al. (1998) highlighted a lack of understanding of the processes accountable for developing TCs, in addition to inconsistent GCM results. They suggest two approaches to forecasting TC frequency in a world greenhouse-induced. These approaches include predicting how environmental capacity sustaining TCs may change, and predicting how frequency and strength of initiating disturbance may change.

Impacts of global warming in TC activity is not the purpose of this research. However, these empirical any possible change in intensity or/and frequency of TCs will affect the TC rainfall contribution over the Unite States.

The focus of this research is the investigation of overall TC rainfall seasonal contribution in the United States.

Specific objectives are:

- Investigate the overall TC rainfall monthly and seasonal contribution in the U.S., comparing results with previous studies.
- Investigate possible relationships between TC rainfall and climate indices such as ENSO and AMO.
- Assess impacts of ENSO and AMO with the number of TCs days in two periods (1931-1960, 1961-2007), the geographical variability of major storms, and TC rainfall trends during 1960-2007 and its correlation with ENSO and AMO.

The second objective of the research was to investigate the relationship between tropical cyclone rainfall volume and the El Niño Southern Oscillation and the Atlantic Multidecadal Oscillation. This objective was aimed at providing important information regarding how those climate phenomenon are correlated with the distribution of tropical cyclone rainfall over the eastern UNITED STATES from 1960-2007. Precipitation trends were analyzed using records from 717 Historical Climate Network stations.

The body of this dissertation consists of three sections (Chapters II to IV), each of which represents a paper in preparation for submission to international scientific journals. As such, each section contains its own introduction, methods, results, and conclusions. A complete list of references is included at the end of this dissertation. Chapter II focuses on the spatial distribution of tropical cyclone rainfall over the Eastern United States during hurricane season (June-November) from 1960-2007. Chapter III and Chapter IV addresses tropical cyclone rainfall, and its correlations with major climate teleconnections. Chapter III analyzes the overall TC rainfall seasonal contribution in the United States, investigates possible relationships with climate indices such as ENSO and AMO, and identifies trends in TC rainfall. Chapter IV analyzes the volume accumulated by TC rainfall over eastern U.S. between 1960 and 2007and the correlation with ENSO and AMO. The final chapter (V- Concluding Remarks) provides an overall interpretation of the research results, as well as outlines the significance and contribution of the research presented here. This chapter also briefly describes future work, which includes case studies of individual tropical storms and their contribution to seasonal rainfall over the eastern United States.

II CONTRIBUTIONS OF ATLANTIC TROPICAL CYCLONES TO MONTHLY AND SEASONAL RAINFALL IN THE EASTERN UNITED STATES -1960-2007

INTRODUCTION

Tropical Cyclones (TCs) are the most devastating of natural disasters with huge economic losses [e.g. Hurricane Katrina, 2005 and Andrew, 1992] and loss of human life (Blake, Rappaport and Landsea 2007). TCs cause disruptions in tourism, cripple transportation, cause delays in production in the oil and gas industry, damages properties and business, and disrupts coastal ecosystems (Lyons 2004). Extreme rainfall from TCs also brings additional hazards such as flooding and mudslides, as well as compromising the quality of available water sources (Cry 1967). The overall impact of these hazards on the economy and human life is often influenced by the size of the population impacted by the storm. Increasing population rates in coastal areas over recent years underscore the magnitude of disastrous consequences, forcing societies and governments to reduce social vulnerability to hurricanes (Landsea, et al. 1999; Elsener and Kara 1999).

TCs often represent a substantial part of the annual rainfall in the southern United States coastal zones, but show a high level of decadal variability (Karl, et al. 2005). Nevertheless, TCs contribute significantly worldwide to monthly and seasonal rainfall (Cry 1967; Lyon and Camargo 2008). In addition to the obvious coastal zone impacts of hurricanes, there can also be substantial impacts far inland. For example, Emmanuel (2005) pointed out that the highest hurricane death tolls in the U.S. result from inland flooding, and a National Hurricane Center study (Rappaport 2008), showed that 59% of United States TC deaths from 1970 to 1999 were caused by freshwater flooding inland.

Similarly, at interior locations, TC rainfall contributes to river systems, replenishes reservoirs, and boosts groundwater supplies (Middelmann, 2007). Understanding TC behavior is critical to minimizing economic loss through urban planning and mitigation efforts such as engineering levees, dams, and buildings (Rodgers, Adler and Pierce 2001; Middelmann, 2007).

TC RAINFALL DISTRIBUTION

Rain accumulated from a hurricane in a single location may contribute, within 2 or 3 days, 50% to 100% of mean annual precipitation (Simpson and Riehl 1981).The amount of rain at a given place is determined by four factors: a) amount of water vapor in the air, b) ratio of ascending air in the atmosphere, c) vertical extension of the updraft, and d) duration of the updraft (Emmanuel 2005). Nevertheless, the rate of TC precipitation diminishes dramatically after landfall. After landfall, TC rainfall is locally modulated by geographic features, especially mountains (Simpson and Riehl 1981;Hart and Evans 2001;Emmanuel 2005).

TC forward velocity directly affects the amount of rainfall more than TC intensity. Larger storms with a slow forward velocity tend to produce the most rainfall at any given location (Emmanuel 2005).Tropical storm Claudette in 1979 is an example of a weak storm; however, it produced local rainfall amounts of 30 + inches over Texas and Louisiana, and 43 inches west of Alvin, TX (Rappaport 2008). Another example of a weak, slow moving storm with heavy rainfall is tropical storm Alison in 2001, which produced 36.99 inches at the Port of Houston (Rappaport 2008).

STATEMENT OF PROBLEM

George Cry (1967), in his pioneering study about the contribution of rainfall associated with TC to annual precipitation, found that from 100 miles to 300 miles inland, 10-15% of the precipitation was associated with TC. Glenson (2006) found a similar pattern of TC rainfall contribution between 1950 and 2004; coastal regions received 8-16% and near-coastal regions 4-12%. Gleason’s analysis, similar to Cry, pointed out that the strongest TC contribution to monthly rainfall occurred between August and October, but with regional variations in that contribution. The amount of precipitation related to tropical storms and hurricanes varies not only spatially, but varies greatly by decade and represents a substantial part of the annual precipitation in the Southeast coastal zone (Karl, et al. 2005). Recent work by Knight and Davis (2007) also found similar results to Cry. In addition, Knight and Davis showed that tropical rainfall increased over much of the study region from 1980 to 2004.

Even thou the cited studies showed close results, they have a different period, number of stations, and methods. In addition, the TC interannual and interdecadal variability could affect the TC rainfall contribution regionally. A lager number of reliable weather stations (USHCN), long period (48 years), and a robust methodology to classify TC rainfall were used to identify the TC rainfall contribution over eastern United States.

The objectives of this study are to:

1. Develop a climatology of TC affecting the United States from 1960-2007,
2. Compare the storm track density between Cry (1967), ranging from 1931-1960, and the more recent period 1960-2007,
3. Determine the TC rainfall contribution to the total rainfall by month and season (June to November) from 1960 to 2007 with a denser rain gauge network than that implemented in Cry (1967), and Knight and Davis, (2007).

DATA AND METHODS

This research implemented data from the HURDAT dataset, including the track and the intensity of each storm from 1931-2007 (Jarniven et al.1984). The year 1931 serves as the starting point because Cry’s (1967) work also began at the same time and this allowed for direct comparison with late period. Hurricane season in the Atlantic basin officially begins in June and extends through November (Landsea, et al. 1999), though there are some outliers. TC frequency in the Atlantic Basin shows that 97.5% of all storms occurred from June 1 to November 30. This result is based on the National Hurricane Center dataset (Historical Hurricane Tracks from 1851-2007), and can be downloaded from the NHC web page (http://maps.csc.noaa.gov/hurricanes/download.jsp). As a result, this study will only focus on storms occurring during hurricane season from 1 June to 30 November.

Tracks were included as long as the HURDAT dataset maintained it as “tropical,” as many TC transform into extratropical systems after making landfall (Keim et al. 2004). Once a storm becomes extratropical, the dynamics within the storm change, hence the rain produced is no longer considered “tropical”. For that reason, tropical storms after becoming extratropical or subtropical systems were excluded from the analysis, resulting in 220 storms left for this study.

Rainfall was divided into two subsets: one with the accumulated TC daily rainfall for each month, called Tropical Rainfall (TR), and the other, the difference between TR and the monthly precipitation, called Non-Tropical Rainfall (NTR), as performed by Cry (1967). As noted, once a storm becomes extratropical, it is classified as NTR. In addition, rainfall produced by subtropical storms is also classified as NTR.

Previous research provides some guidance regarding the size of the rainfall swath produced by TC. For example, Cry (1967) considered rainfall to be tropical within the limits of the TC circulation ranging from under 100 kilometers to over 800 kilometers, depending on each storm’s characteristics. Rao and Macarthur (1994) placed a grid over each storm and determined the rainfall within each grid cell. Gleason (2006) used a simple partition method to consider rainfall associated with TCs, considering any rainfall

≤ 600 km from the center of the storm as tropical rainfall.

Due to the asymmetrical structure of TC, rainfall shields cannot be represented by a circle (Matyas, 2007). However, Englehart and Douglas (2001) found that in 90% of cases the TC’s rainfall occurs within 600 km from the center, and they used a 550 km radius from the center of each storm to assign surface weather stations as receiving TC-derived rainfall data. Knight and Davis (2007) based their study on all rainfall data associated with the tropical storm, even after becoming extratropical or associating with a frontal system. This approach could have overestimated the contribution of TC rainfall in the monthly totals. In this study, a conservative approach was used in considering tropical rainfall related to the distance of the center of TC. Using guidance from these previous efforts, a buffer of a 500 km (310 miles) radius centered on each storm was used to select the area affected by the tropical precipitation. TC precipitation was to be assumed symmetric around the storm center (Larson, et al., 2005). The 500-km criterion is an operational definition to reduce the influences of other meteorological systems such as approaching extratropical cyclones

Rainfall data are extracted from monthly rainfall observations from the United States Historical Climatology Network Monthly Precipitation and Temperature Data USHCN (Williams et al., 2007). This dataset contains 1221 high-quality stations from the U.S. Cooperative Observing Network within the 48 contiguous United States, and has undergone extensive quality assurance checks and includes only the most reliable and unbiased long-term records. Daily precipitation was obtained for the same stations through the Southern Regional Climate Center (SRCC) Applied Climate Information System (ACIS). TC-related precipitation was considered any precipitation produced by hurricanes and tropical storms for all storms making landfall in the Eastern U.S., and for all storms that were within an offshore distance of 500 km. No subtropical systems were considered as denoted by the National Hurricane Center (NHC) in the best-track dataset.

All weather stations were plotted by month and clipped by the storm's buffer region using ArcMap 9.2. Figure 1 provides an example of the clipped stations that fell under the 500 km buffer. Figure 1a shows the path of Hurricane Camille in 1969 with the tropical buffer area as well as the stations within this area, and the storm classification (Saffir-Simpson). Figure 1b represents the 500 km buffer for all storms used to select 34 states used in this study, which includes 717 USHCN stations. However, despite the fact that the states of New Mexico, Colorado, and Nebraska were within the storm buffer, they were not included on this study because TC rainfall contribution are less than 1% of the total precipitation.

Excel was used to calculate basic descriptive statistics. ArcMap was used to display those stations and to perform spatial analyses. The simple Kriging quartile tool was used to create an interpolated surface (Chapman & Thornes, 2003). Kriging was chosen as the interpolation method because it assigns more influence to the nearest data points in the interpolation of values for unknown locations and generally creates smooth patterns, with fewer bull-eyes than many other interpolation methods (Anderson 2001). Line density is an ArcMap tool used to calculate the density of linear features in the neighborhood of each output raster cell. Density is calculated in units of length per unit of area. Using the NHC best track data (location and storm intensity at 6-hour intervals), the track density (TD) was computed for each month. TD was obtained using ArcGis 9.2 spatial analysis tool: line density, with a cell size of 0.2° x 0.2° lat/long. Some researchers have used 0.5° x 0.5° lat/long grid in storm track density analyses (Lyon & Camargo, 2008), however, the cell size of 0.2° x 0.2° lat/long was chosen to capture a higher resolution in storm track variability The TD was used to compare changes in monthly tracks from 1931-1960 (the period analyzed by Cry (1967)) and from 1960-2007.

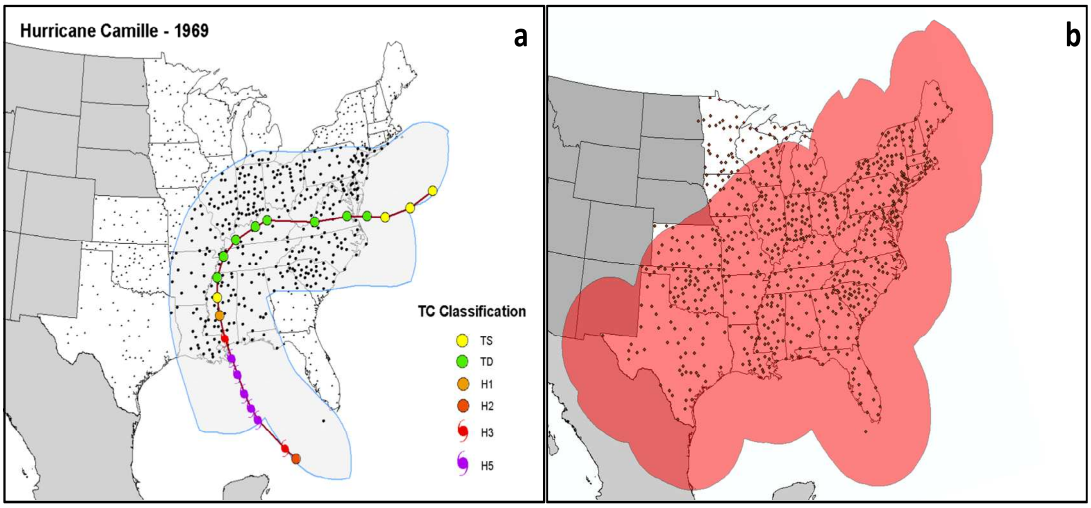


Figure 1 : (a) Hurricane Camille track (solid line) with the 500 Km buffer (shadow area). Dark dots represent the stations under the TC rain buffer, and the light dots represent stations in the study not affected by Camille; (b) Buffer of all storm 500 km from 1960-2007 (red area). Dark dots represent the 717 stations included in this study.

RESULTS

Tropical Cyclones Affecting the United States

Figure 2 shows a time series of storm counts from 1960 to 2007, a period that averaged 10.4 named storms per year, higher than the 9.8 found by Landsea et al. (1999) from 1950 through 1990. Webster (2005), using time series for all basins from 1970 to 2004, found no trend in hurricane frequency, though Figure 2 does show an increase in storms counts beginning in the mid-1990s. The five-year moving average has a positive trend after 1995, and the Kendall tau b test showed a positive trend (p=0.01) in the total number of TC. However, individually any TC class (TS, Cat 1, Cat2…etc.) showed a statistically significant trend.

Figure 3 shows the frequency of landfalling storms summed as storms either making landfall or coming within 500 km of United States coast from 1960-2007. The study period shows a total of 220 storms - an average of 4.6 storms per year. Similar as found in Figure 2, the 5-year moving average shows a positive trend after 1990, however, no trend was found in the time series, based on Kendall tau b.

The period of 1960-2007 had 287 hurricanes and 219 tropical storms; however, only 50 hurricanes and 104 tropical storms have landfall, as defined by the National Hurricane Center, in the eastern U.S. between June and November (Table 1). In addition, 76 TCs were included in this study that tracked within the 500 km threshold to shore bringing the total number of storms included in this study to 220. The study period displays annual variability of hurricanes and tropical cyclones, whereby in August and September 62% of all hurricane and tropical storm landfalls in the U.S. took place.

Storm Day

Storm days (SDs) are defined as the total number of days that a TC center either crossed or came within 500 km of the coast of the United States (only Atlantic Basin storms). A single storm day can have more than one storm affecting the U.S. at the same time. Figure 4 shows the number of SD by year. The moving average shows a negative trend from the 1970s to the early 1990s and a positive trend after that. The year 2005 had 43 SDs and 1985 had 31 SDs, with an average of 13.7 SDs per year. Figure 5 shows the monthly percentage of SDs, with September having the highest seasonal percentage at 45%.

Storm Track Density

The shaded areas in Figure 6 represent the high line density. Density is calculated in units of length per unit of area. The default unit of area is one square map unit. Thus, the units of line density are map units per square map unit, or 1/map units. Density is in meters (of line length) per square meter (Silverman, 1986**).**

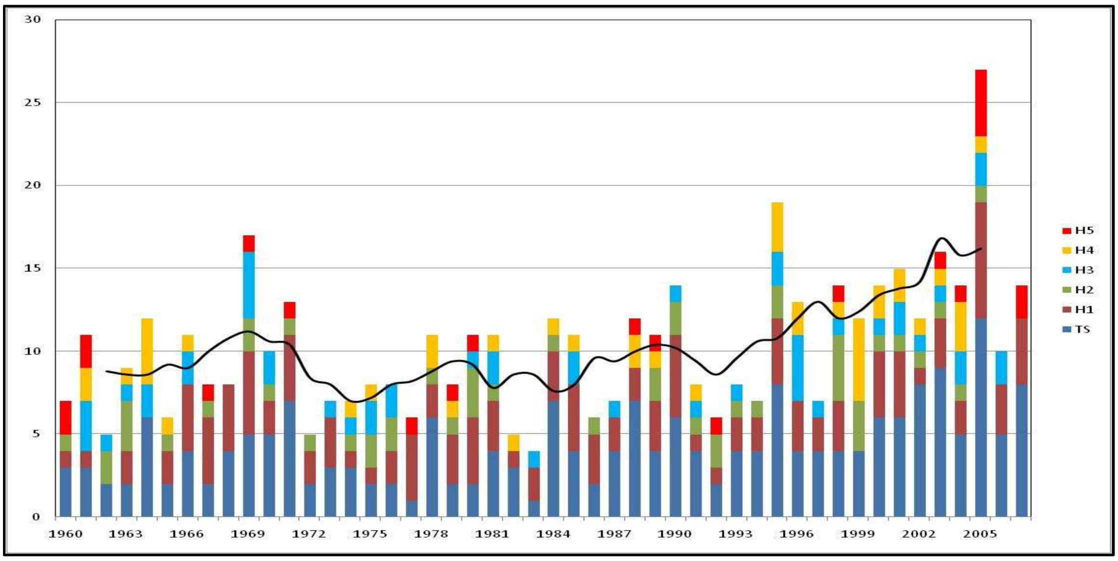


Figure 2: Annual number of named tropical storms over the Atlantic basin for the period of reliable record from 1960 to 2007. The five-year running mean (solid line) is superimposed on the time series.

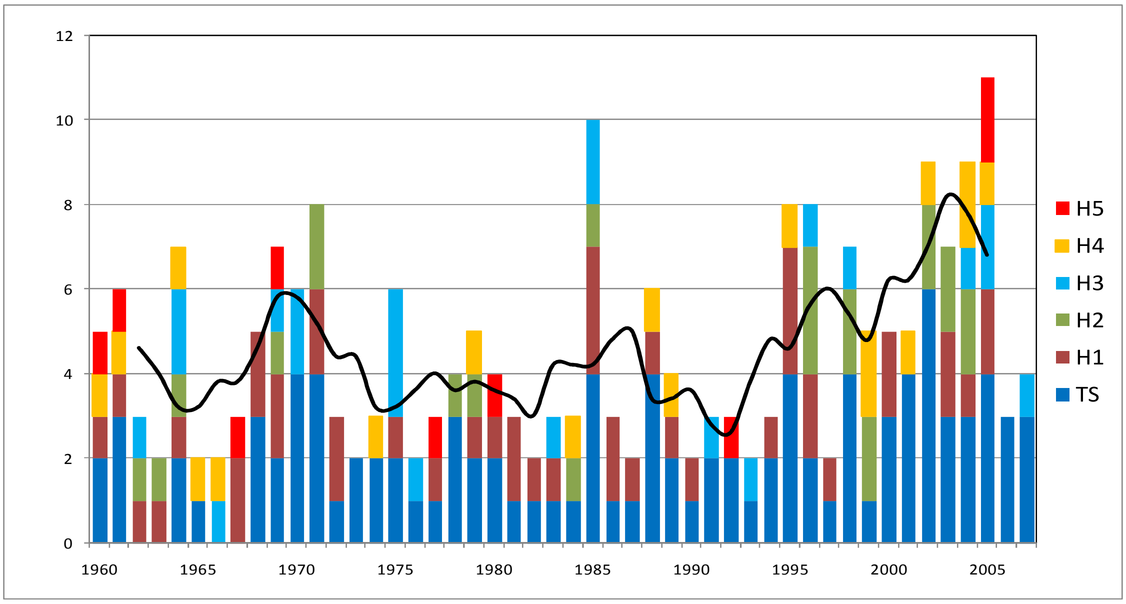


Figure 3: Annual number of storms within 500 km from the U.S. coast from 1960 to 2007.The 5-year running mean (solid line) is superimposed on the time series.

Table 1: Frequency of hurricanes and Tropical storms between 1960 and 2007 in the Atlantic basin.

All Storms

	TS/TD	H1	H2	H3	H4	H5	Total
JUN	23	6		1			30
JUL	26	16	3	4	1	2	52
AUG	58	26	14	16	15	8	137
SEP	66	36	21	23	23	9	178
OCT	37	25	10	5	3	3	83
NOV	9	13	2	1	1		26
Total	219	122	50	50	43	22	506

U.S. Landfall

	TS/TD	H1	H2	H3	H4	H5	Total
JUN	16	1					17
JUL	12	2					14
AUG	27	7	3	3	1		41
SEP	35	12	10	1	1	1	60
OCT	10	4	1	2			17
NOV	4	1					5
Total	104	27	14	6	2	1	154

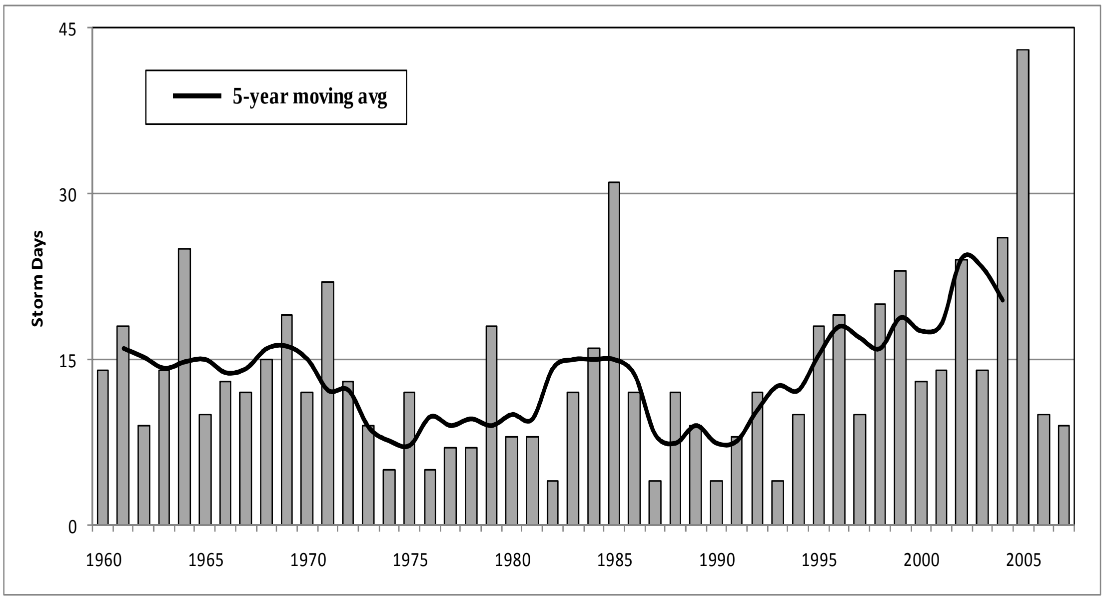


Figure 4: Storm days from 1960 to 2007 and 5- year moving average (bold line)

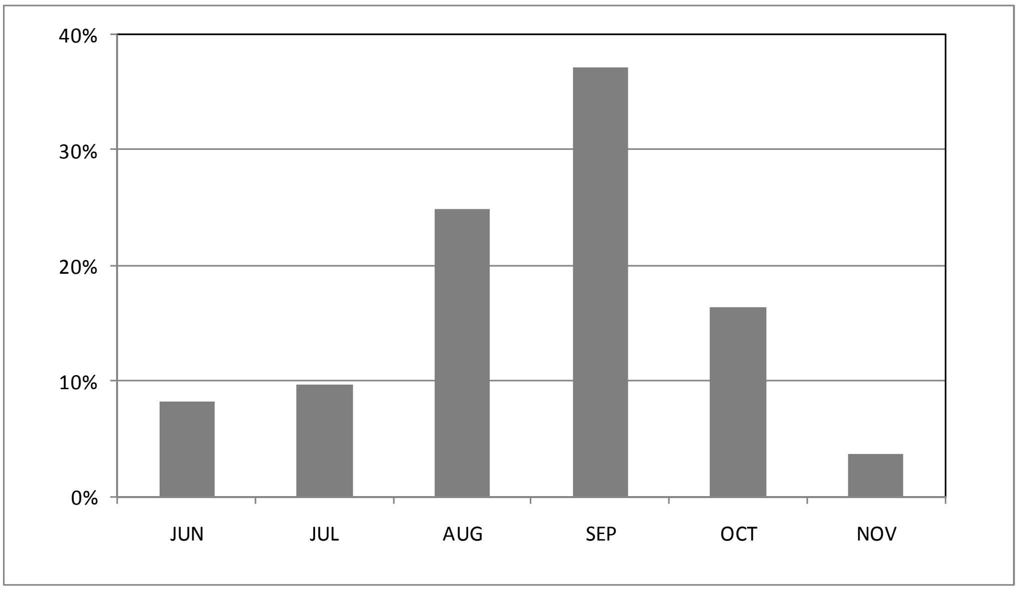


Figure 5: Monthly percentage of storms days from 1960-2007

- **June**

Storm track density showed regions with high values in the Gulf of Mexico (Figure 6). The average of June tropical storms per year during the period 1960-2007 was 0.45 storms, close to Cry's 0.56 storms for 1931-1960. Tropical storms represent 70% of all storms, minor hurricanes 18%, and major storms 12% during that 1931-1960 period. June had 53 SDs with an average of 1.8 SDs per year. TCs in June during 1960-2007 were characterized by a two storm track regions, one in Texas, and another from East Florida to South Georgia and the Carolinas. June of 1968 had three storms and 1986 had two storms, and 19 years had only one storm. Tropical storms (TS and TD) represent 69% of all storms, minor hurricanes 26%, and major hurricanes 5%. The study period showed 54 SDs with an average of 1.1 SDs per year.

- **July**

Storm track density in during 1931-1960 showed two regions one in Texas and Louisiana coast and another high density along the South Carolina coast. The July storm year average, from1960-2007, was 0.46 storms per year, smaller to Cry's 0.63 storms per year for 1931-1960 period. The number of SDs had increased 12% relative to June. Tropical storms in this period represented 84% of all storms and minor hurricanes (16%). July storm tracks showed four high-density regions; one in the Gulf of Mexico, one over Alabama, and two on the Carolina coast (Figure 6). During 1960-2007 period tropical storms represented 59% of all storms, minor hurricanes (32%) and major hurricanes (9%). In July 23% of the years (1960-2007) had one TC, and 8% had more than one. In 2005, a record of 5 storms occurred. The later (1960-2007) period had storms travelling further inland compared with the earlier period (1931-1960).

- **August**

Figure 6 shows two high-density regions in the storm tracks, one in the Gulf of Mexico and another on the Carolinas' coast. The number of SDs rose to 193 with an average of 5.8 SDs per year**.** August exhibited an average of 1.4 U.S. landfalling storms per year during 1931-1960. The year of 1933 was the most active with four storms per year. This period was characterized by a higher number of tropical storms (53%), followed by category 1 and 2 hurricanes in SFHS (33%), and major hurricanes with 14%.

The density tracks (Figure 6) during the period 1960-2007 were concentrated in eastern Florida and from South Carolina to Virginia. The track density during Cry's study moved from the Gulf of Mexico to the East Coast during the second period. August shows an overall average of 1.2 storms per year, lower compared to Cry's period. The year of 2004 had the most TC frequency with 5 storms. However, thirteen years had no storms make landfall at all, even using the 500 km from the coast criteria. TS represent 48% of all storms, minor hurricanes (29%), and major hurricanes (22%). The number of SD in August jumped to 163, however with an average of 3.4, lower than Cry's study (5.8).

- **November**

November is the lowest TC activity month with an average of 0.3 storms per year during 1931-1960. Only 8 storms were reported in 30 years, and that could be result of the observation system in that period, as pointed out by Landsea (1999). TS represented 75% of all storms, minor hurricanes 12%, and Major hurricanes 13%. This month has the lowest SDs with only 21 SDs and an average of 0.7 storms days per year.

The TC track density showed a shift closer to shore between Cry's study (1931-1960) and the period of 1960-2007 (Figure 6). This period showed an average of 0.2 storms per year, lower than Cry's. Only ten years had one storm, and 38 years with no storm landfalls. TSs represents 60%, minor hurricanes 20%, and major hurricanes 20%. The number of storm days in November is the lowest of the hurricane season (June – November). The total is 24 SDs and an average of 0.5 storms days per year, where 1994 was the maximum year with six SDs.

Percentage of Tropical Rainfall Contribution

The percentage of tropical rainfall related to total monthly precipitation was determined. To compare results in this study to Cry (1967), procedures used here were applied to the period 1931-1960; any storm within a 500 km distance of the coast was counted. That procedure will produce in some months a higher number of storms than Cry computed. Cry's results were published before Herbert Saffir and Robert Simpson developed their Saffir-Simpson Hurricane Scale – SFHS (Blake, Rappaport and Landsea 2007). However, the Saffir-Simpson scale was applied to Cry's study of storms to compare to more recent studies.

- **June**

June shows that the maximum average rainfall occurs in the Florida .

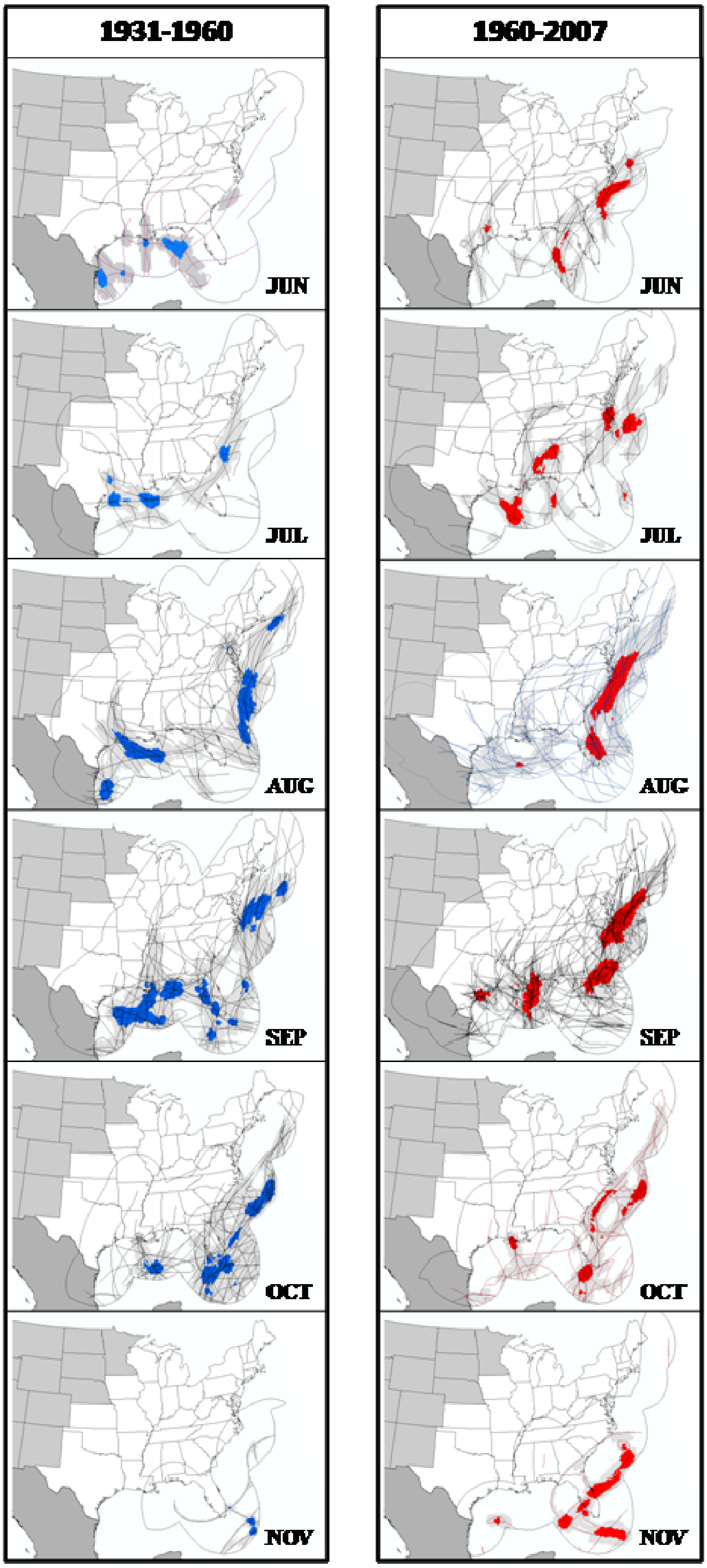


Figure 6: Storm track density was calculated for a cell size of 0.2° x 0.2° latitude/longitude, and shows the density of linear features in the neighborhood of each output raster cell. Each month during the Atlantic hurricane season (June to November) is displayed for two study periods. The left column displays TDs during Cry's (1967)1931-1960 study period. The shaded blue regions represent the highest line density. The right column represents the TDs during 1960-2007 study period. Shaded red regions represent the highest line density

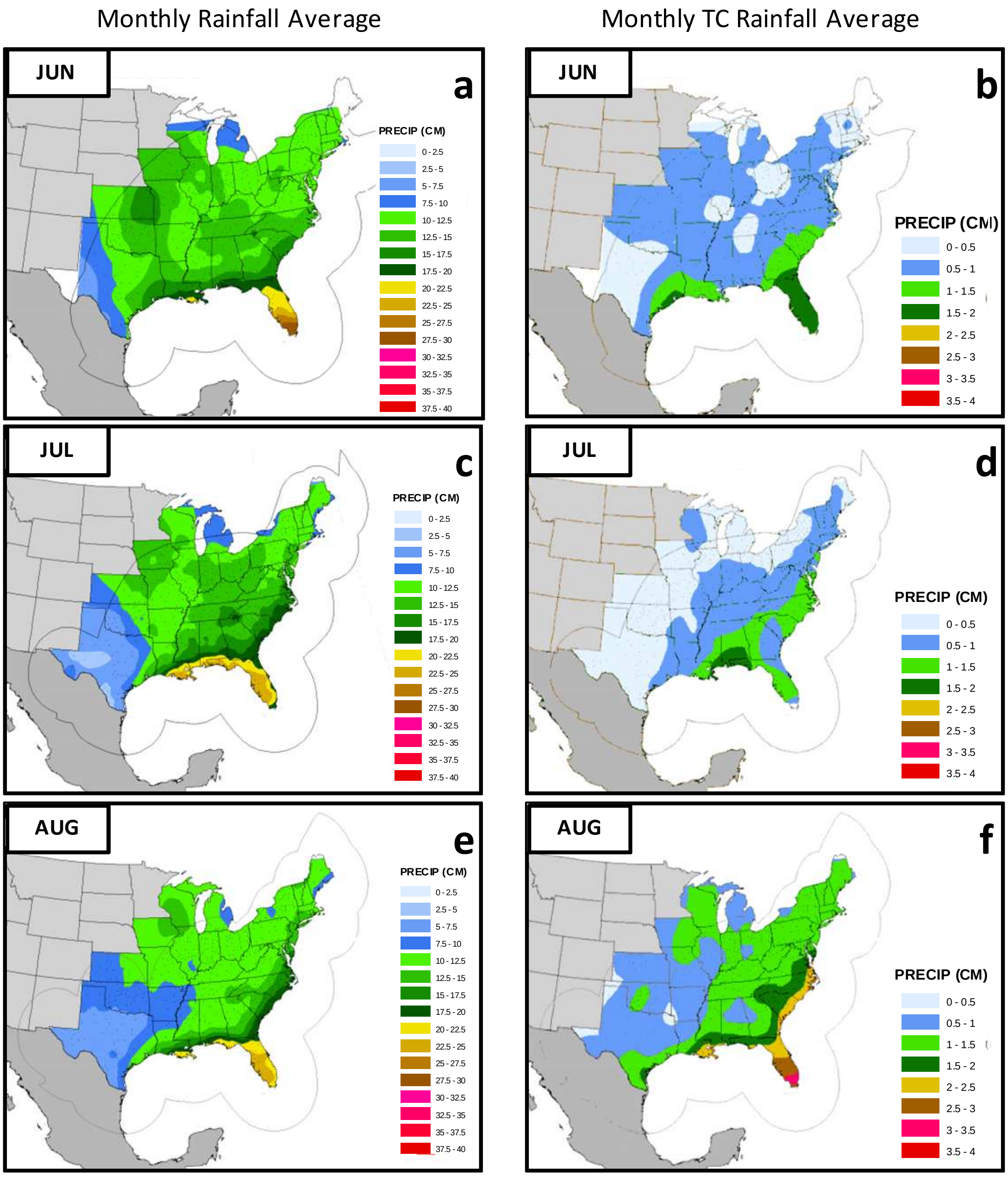
Panhandle and southern Louisiana (20 to 30 cm), and TC rainfall in Florida and along the Texas coast at 1.5 to 2.0 cm per year (Figure 7**a).** West Texas receives the least rainfall (tropical and non-tropical). The tropical rainfall average showed two maximum regions, one on the Texas coast and the other at Florida and South Georgia (Figure 7b). The maximum percentage of TC rainfall was found on the Texas coast, north Florida and South Georgia at 9-12% (Figure 9- June). That high percentage is related to the lower non-tropical rainfall in those regions. The geographical pattern agrees with Cry's findings, however, the 1960-2007 analysis showed a percentage of 6-9% east of the Appalachians, higher than Cry (1967) and Knight and Davis (2007). That difference may be related to variations in the study periods, as well as variability in the number of storms between the study periods.

- **July**

The total rainfall average shows that the Gulf of Mexico Coast received the maximum values followed by the Atlantic Coast, and Texas the least amount of rainfall (Figure 7c). The average TC rainfall shows a maximum value (1.5 to 2.0 cm) from east Louisiana, South Mississippi, South Alabama and West Florida (Figure 7d). The maximum TC percentages (Figure 9 – July) show a region from the Gulf crossing Georgia, the Carolinas, and extending down to Massachusetts (6-9%); these are roughly the same values found by Knight and Davis (2007)

- **August**

Florida receives the maximum precipitation from TC in August with 20 to 25 cm, while southern Louisiana receives 20 cm on average (Figure 7e). Texas is the region with the least precipitation (5cm); however, the coast receives more than 10 cm. Tropical rainfall showed a maximum value in the Florida Panhandle and in N. Carolina (3.9cm).



Monthly Rainfall Average

Monthly TC Rainfall Average

Figure 7: June to August monthly rainfall average and TC monthly rainfall average from 1960-2007. Each month shows the storm buffer region (light blue line). Left column represents the seasonal rainfall average and the right column the TC seasonal rainfall average.

TC rainfall decreases rapidly inland, but terrain features could intensify rainfall, such as that shown in the Appalachians in the Carolinas (Figure 7f). TC average percentage (Figure 9 - August) presents three regions with more than 12%: 1) South Carolina and Eastern North Carolina, 2) Southern Florida, and 3) Southern Texas, where the maximum percentages are found in Texas (Corpus Christi and Falfurrias) with 22%. Most of the study region receives between 9 to 12%. The pattern found in the 1960-2007 period showed some general similarity with Cry's results. However, Cry (1967) found a maximum region in South Texas 30% tropical rainfall in August, whereby this study has it at 15%. Differences in both studies can be explained by the storm tracks in Cry's study, methodology, and monthly rainfall (dry or wet seasons). These results compared to Knight and Davis showed similar values only in southern Texas. The maximum percentage in the North Carolina coast (>24%) found by Knight and Davis can be explained by the number of stations on their study (84 station) compared this study (717 stations), and the TC frequency in both studies as a result of the time period (25 years on their period versus 48 years on this study).

- **September**

Monthly rainfall averages shows that the Florida Panhandle receives the maximum with more than 20 cm (Figure 8a). Rainfall decreases rapidly inland with values higher than 15 cm on the coast (from Texas to Virginia) to less than 5cm in western Kansas and western Oklahoma. TC rainfall average has higher values on the coast (3 to 6 cm), decreasing rapidly inland to less than 1cm. Coastal North Carolina shows a maximum value of 7.6 cm. Local and regional topographic features could alter the TC rainfall values. Most of the higher TC rainfall is found east of the Appalachians (Figure 8b). September shows two regions that receive the largest TC rainfall contribution; one in south Alabama with 30-32%, and the other in North Carolina and Virginia with 30-34% (Figure 9 -September). These results were similar in pattern to Cry's findings; however, there are some discrepancies in values. Cry found 45% from the Virginia coast to coastal New Jersey, whereby results here show less than 35%. Overall, the period of 1960-2007 presented higher TC rainfall contributions as compared to the Cry and Knight and Davis studies. The study period had an average of 1.5 storms per year; smaller than during Cry's study, which had 1.9 storms per year. TC frequency has a maximum of 5 storms in 2002, 4 storms in 1971 and 1998, and 14 years with no storm landfalls.

- **October**

During October, the maximum rainfall average was found in South Florida, followed by Eastern Texas and Western Louisiana (Figure 8c). The East Coast from Florida to North Carolina received the maximum amount of TC rainfall (>2cm) followed by South Louisiana and West Florida (Figure 8d). Tropical rainfall percentage has a maximum value over South Carolina (similar to Cry and Knight and Davis), decreasing further inland. East Louisiana shows another higher value (15-18%) (Figure 9- October).

Overall, October 1960-2007 showed the greatest reduction in TC rainfall contribution, when compared to 1931-1960. Knight and Davis founded a higher value of 15%-18% TC contribution in the South Carolina coast, and the period of 1960-2007 had 21% for the same region.

- **November**

The maximum rainfall average area is found in Maine (>20cm), however; North. Louisiana and West Mississippi has the second highest rainfall (>15 cm) (Figure 7e). Rainfall was altered by frontal systems or geographic features other than tropical systems.

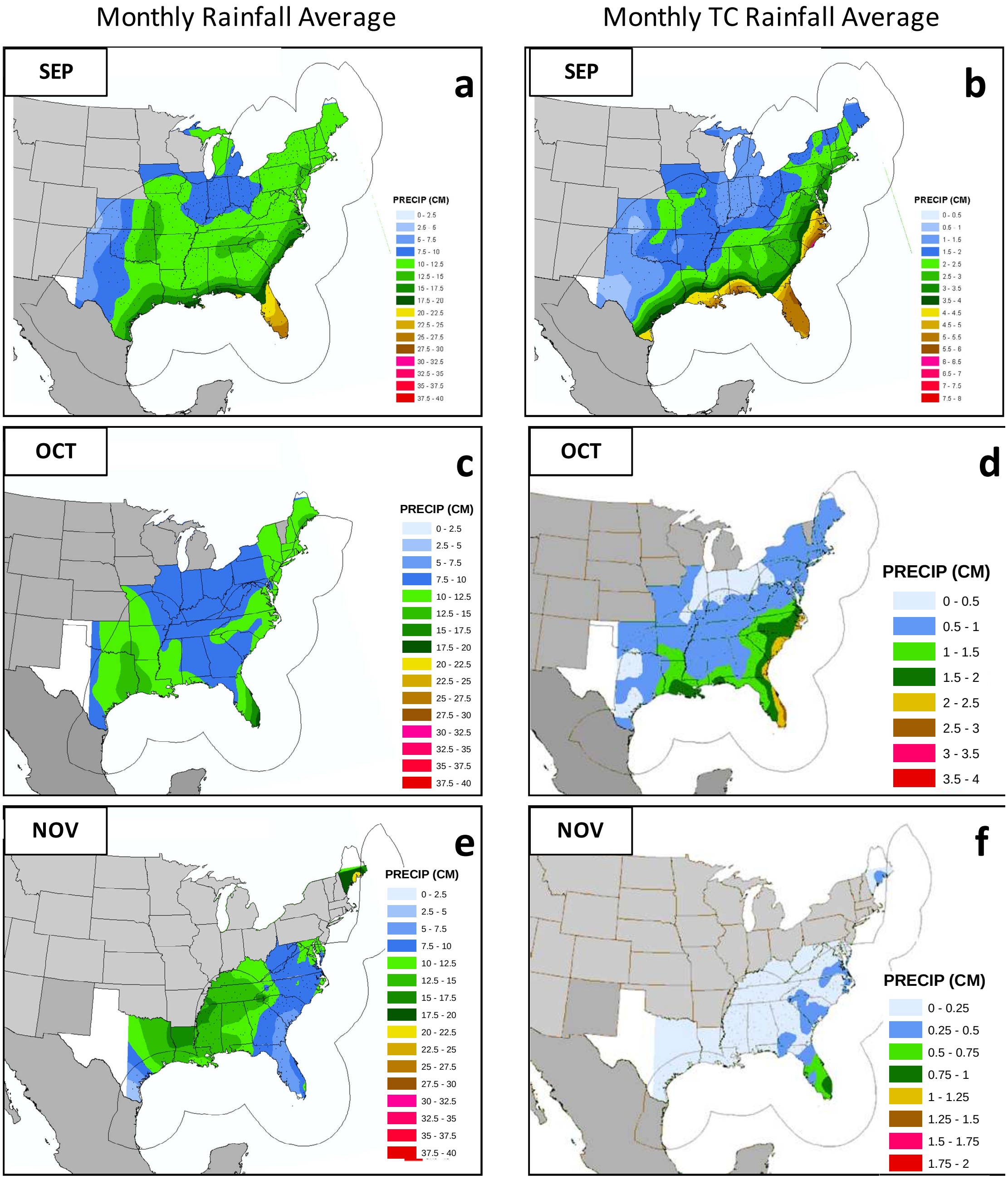


Figure 8: September to November monthly rainfall average and TC monthly rainfall average from 1960-2007. Each month shows the storm buffer region (light blue line). Left column represents the seasonal rainfall average and the right column the TC seasonal rainfall average.

Tropical systems produced more rainfall in South Florida (Figure 8f). The maximum percentage is 9-12%, which is close to the value founded by Knight and Davis (2007).

TC Seasonal Rainfall Distribution

Seasonal rainfall (tropical and non-tropical) shows South Florida with the largest value (>120 cm), followed by the Gulf of Mexico and the coast of North Carolina (Figure 10-a). West Texas and West Oklahoma have rainfall totals lower than 50cm. Generally, rainfall totals diminished further inland; however, local features such as mountains could locally increase the amount as is seen on the border of Georgia, Tennessee, and North Carolina. TC rainfall maximum occurs in the Florida Panhandle, followed by Louisiana and North Carolina (Figure 11-a). The TC percentage has a different pattern compared with the TC rainfall. The maximum value is found in south Texas and the coast of North Carolina (14-16 cm), and it decreases when moving inland and northward away from the rainfall source (Figure 11- a). These results are similar to Cry's findings, however, the period of 1960-2007 possessed higher TC rainfall contribution inland than during the 1931-1960 period. For example from the Texas Panhandle to western Kansas were values higher than 8% of TC contribution are shown , suggesting that storms were traveling further inland during the 1931-1960 period (Figure 11-b).

TC Rainfall Contribution Comparison

Figure 12 (a-c) shows the Cry (1967) TC rainfall average contribution (August-October). He combined TC rainfall average of Jun and July on his study and did not considered November TC rainfall. Cry approaches might create some differences compare with this study, and for that, only August to October will be used to comparison between both studies.

- **August**

This month showed that TC rainfall had higher contribution over coastal stations during 1931-1960 compared with 1960-2007 period. South Texas had 30% of TC rainfall during the fist period and 15% during the second period. However, during 1960-2007 TC rainfall showed higher inland contribution, with the 10% isoline crossing Kentucky, western Mississippi, north Texas, and Oklahoma (Figure 9). Several regions presented similar TC rainfall contribution during both study periods: Alabama and Florida Panhandle with 10%, south Florida with 10%, and North Caroline with higher than 12%.

- **September**

Similar to August, September showed higher TC rainfall contribution on the coastal USA stations during Cry's period, and higher inland TC rainfall contribution during 1960-2007 (Figure 9). New Jersey received 45% of TC rainfall during 1931-1960 and less than 30% during 1960-2007. The 20% TC rainfall isoline showed the same pattern in both study periods from Maine, passing east of The Appalachians, to Louisiana. During 1960-2007, the states of Texas, Oklahoma, Arkansas, Tennessee, Kentucky, and from Indiana to west of New York received more TC rainfall contribution compared with 1931-1960.

- **October**

This moth showed a similar TC rainfall contribution pattern during 1931-1960 and 1960-2007.The 10% TC rainfall isoline from Virginia to Louisiana showed similar pattern in both periods. TC rainfall showed higher contribution in coastal stations during the first period, similar as founded in previous months (Figure 12c). However, the north states of the Appalachian region received more TC rainfall contribution during 1931-

1960 compared with 1960-2007.

Seasonal

Cry (1967) analyzed the TC rainfall contribution in the eastern United States from June to November (1931-1960) (Figure 12d). The Coastal Plain region received in average 10%-15% of TC rainfall in both study periods, and the Appalachians, east of the Interior Lowlands, and south of the Great Plains receives less than 5%. Seasonally, TC rainfall contribution presented the same pattern during 1931-1960 (Figure 12d) and 1960-2007 (Figure 11b) periods.

SUMMARY AND DISCUSSION

The average of TC rainfall in the U.S. changes considerably from month to month and it is regulated by each storm's track, intensity and forward movement.

The following bullets are a summary of the findings:

- November receives the least amount of TC rainfall, less than 1cm across the study region (Figure 8f).
- September shows the maximum amount on average, 6 cm in North Carolina (Figure 8b).
- Florida receives the maximum amount of TC rainfall with 14-16 cm (June to November)
- June has the maximum TC rainfall percentages in Texas (15-18%), South Georgia, and Florida.
- North Carolina, Virginia, and South Alabama present more than 30% of TC rainfall contribution in September
- In July, the maximum is positioned over west Florida with 9-12%.
- TC rainfall percentages change geographically from June to November.
- Georgia and South Carolina have more than 18% and Florida has 9-12% in October
- TC rainfall contributes less than 3% in the majority of the region November.
- Seasonally (June to November), South Texas and eastern North Carolina receive the maximum TC rainfall contribution (14-16%).

After September, the number of storms begins to decrease and fewer storms produce inland rainfall. In., a similar result found by Cry (1967). The percent is high in Texas because total non-tropical rainfall is low. In North Carolina, however, the percentage is high because it is most tropically active portion of the U.S. Gulf and East Coasts (Keim et al., 2006).

TC rainfall and its contribution to the monthly total during 1960-2007 showed a similar geographic distribution as found by Cry (1967) and Knight and Davis (2007), even though the total number of SD had some differences between 1931-1960 and 1961-2007.

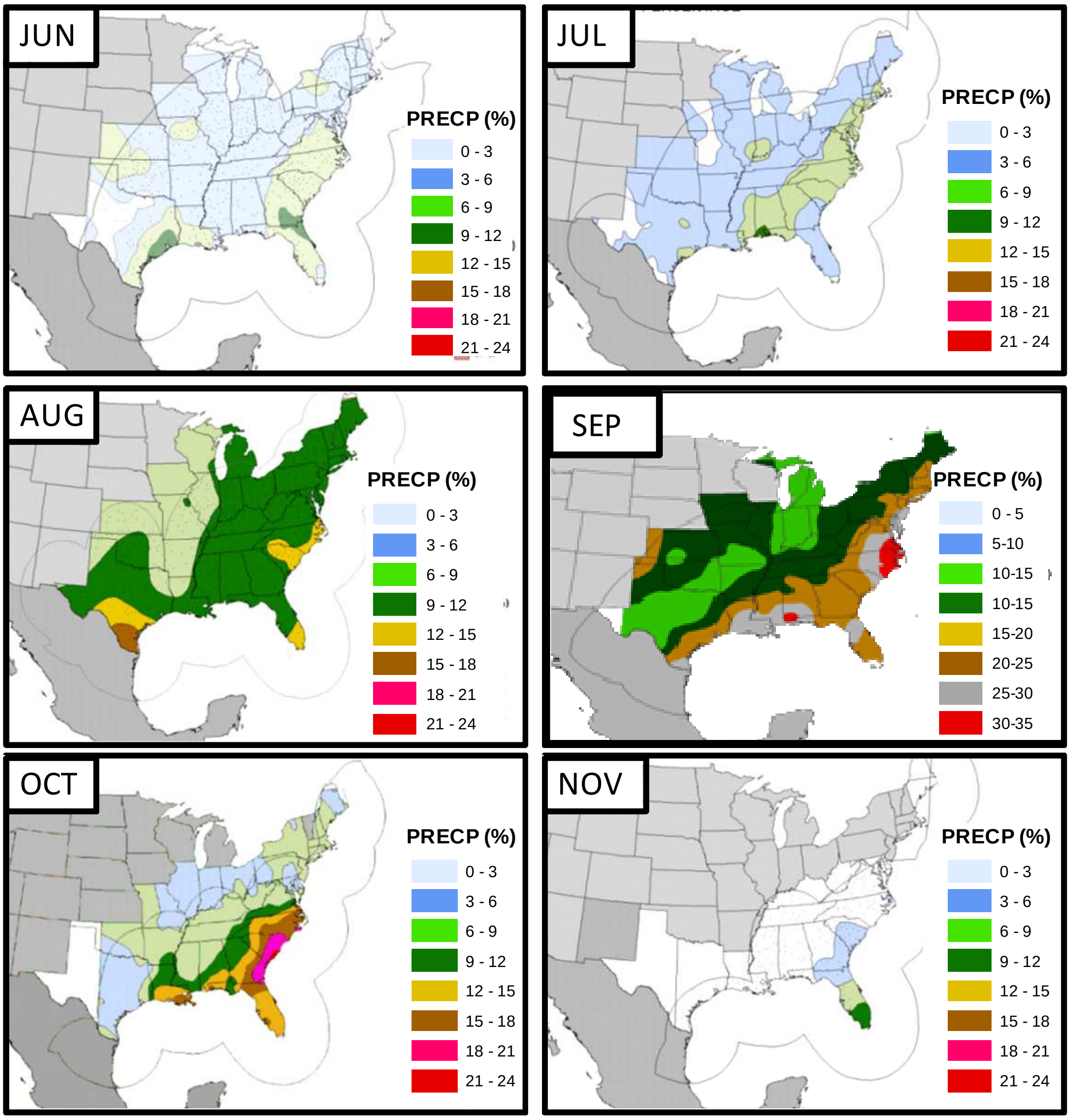


Figure 9: June to November monthly TC rainfall percentage from 1960-2007.

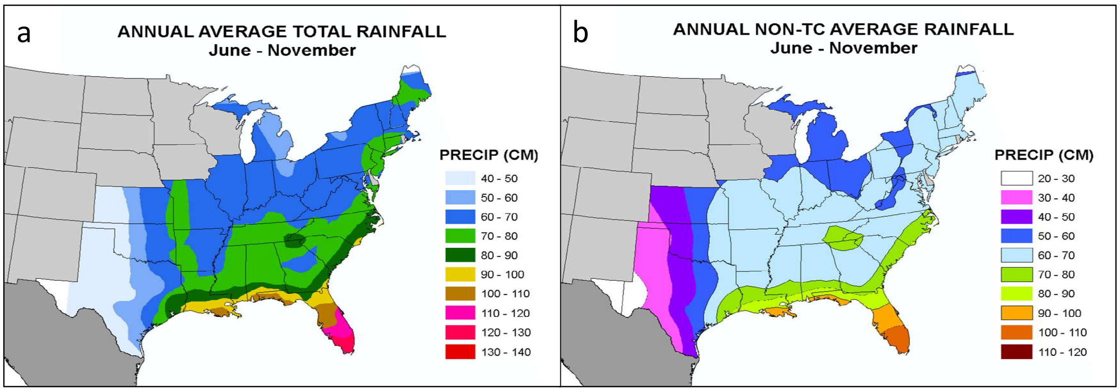


Figure 10: Total rainfall June-November (a) and Non-Tropical (b), from 1960-2007

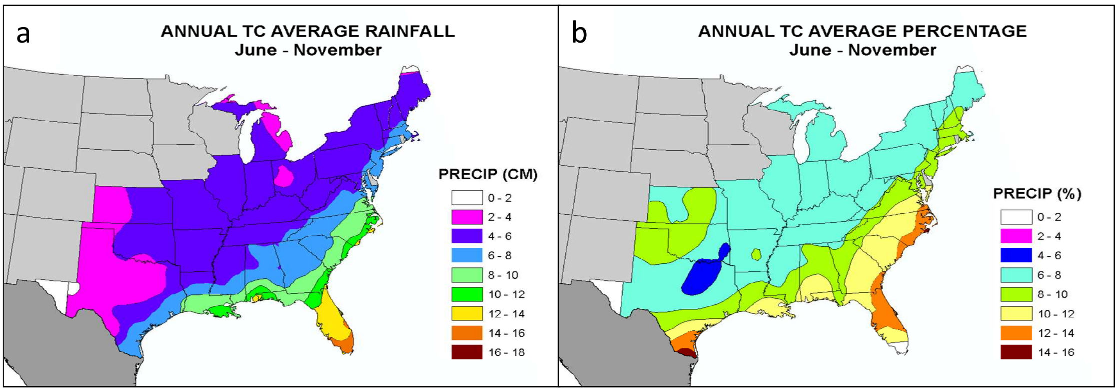


Figure 11: Annual TC rainfall average (a) and annual average percentage (b), from 1960-2007.

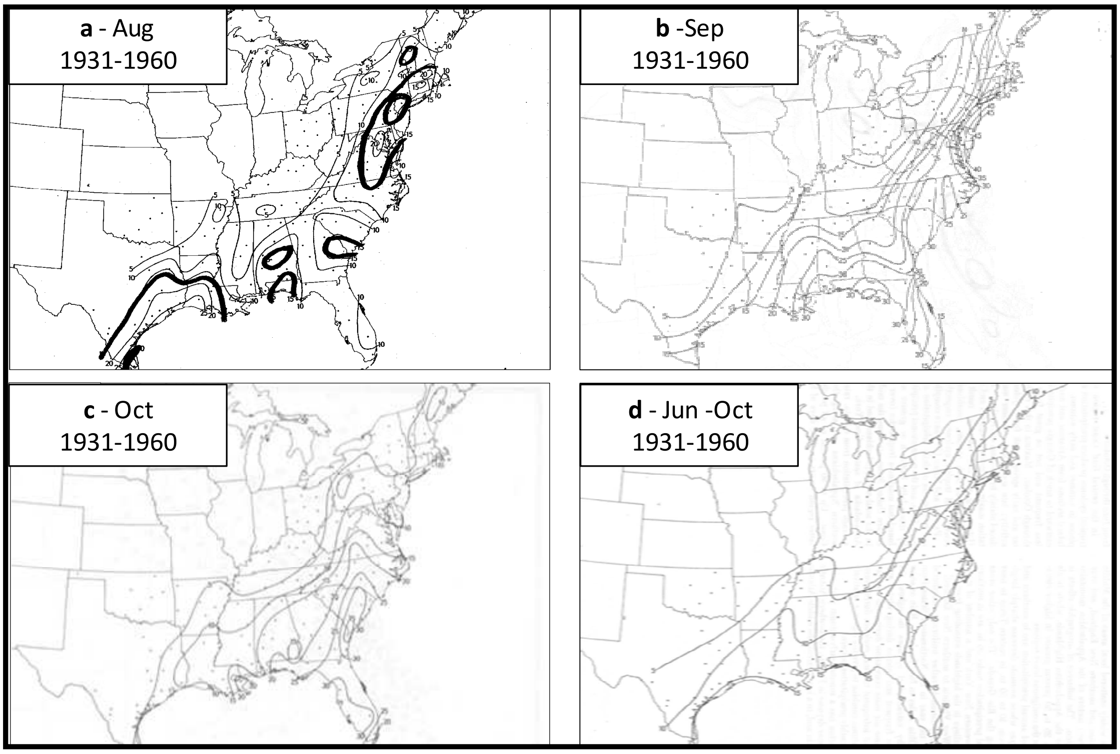


Figure 12 : Tropical cyclone rainfall average contribution from 1931-1960 by Cry (1967). Figures a, b, and c represents the months August, September, and August. Figure d represents the seasonal TC rainfall average contribution (June to October).

III CHARACTERISTICS OF TROPICAL CYCLONE RAINFALL OVER THE EASTERN UNITED STATES

INTRODUCTION

Tropical cyclones (TCs) are the most devastating of natural disasters. They are responsible for causing huge economic losses [e.g. Hurricane Katrina] and loss of human life (Blake et al., 2007). TCs are generally thought of as storms with coastal impacts, e.g., high winds and surge, but they can also bring heavy rainfall much further inland. TC rainfall can often produce flooding and mudslides, but that rain can be beneficial to regions experiencing drought. TC velocity directly affects the amount of rainfall more than TC intensity. Larger storms with a slow forward velocity have a tendency to produce the most rainfall at a given location (Emmanuel 2005). Tropical Storm Claudette in 1979 is an example of this type of weak storm; however, it produced several local rainfall amounts totaling over 76 cm over Texas and Louisiana, and 109 cm west of Alvin, TX (Rappaport 2008). Rainfall associated with TC can extend hundreds of kilometers from the center of the storm and these systems interact with other meteorological phenomenon.

Tropical cyclone activity in the North Atlantic experiences great variability from the intra-annual, the interannual (El Nino-Southern Oscillation), and the interdecadal (Atlantic Sea Surface Temperature - SST) timescales (Keim and Robbins 2006, Gray 2006, Landsea, et al. 1999,). TC seasonality is associated with the seasonal cycle of SST, peaking late summer and late autumn. Landsea et al. (1999) point out that the discrepancy between interannual and interdecadal TC activity with the SST in the North Atlantic Basin may be explained by the interactions of the SSTs with other environmental controls such as El Niño Southern Oscillation (ENSO). For example, El Niño reduces TC activity through an anomalous increase in upper tropospheric westerly winds over the Caribbean basin and the equatorial Atlantic (Gray, 1984). Those anomalous winds increase the tropospheric vertical wind shear creating an unfavorable environment for TC development and maintenance. Many studies have identified an empirical relationship between SST and TC activity where a warmer SST enhances development of TC (Shapiro and Goldenberg, 1998, and Molinari and Mestas-Nuñez, 2003). Various studies investigated the potential effect of long-term global warming on the Atlantic SSTs and the correlation with the number and strength of TC. However, Goldenberg et al. (2001) pointed out that those studies were inconclusive and explained that multidecadal-scale TC variability is greater than the possible small increase in SST by global warming. This study analyzes TC rainfall in the United States and its possible relationship with climate teleconnections such as ENSO and AMO. It will also identify trends in the amount of TC rainfall between 1960 and 2007.

DATA

Monthly precipitation data used in this study were obtained from 717 stations in the U.S. Historical Climatology Network (USHCN), between 1960 and 2007. These station falls within the states that were selected based on the storm track transition from tropical storm to tropical depression, defined by the National Hurricane Center. Previous studies showed that TC rainfall contribution is less than 1% in west of Minnesota and Iowa, and north of Kansas(Cry, 1967, Knight and Davis, 2007).

Figure 13 shows the spatial distribution of these stations. Daily precipitation was obtained for the same stations through the Southern Regional Climate Center (SRCC) Applied Climate

Information System (ACIS) to update the USHCN dataset to 2007. TC-related precipitation was considered any precipitation produced by hurricanes and tropical storms with or without landfall within an offshore distance of 500 km. No subtropical or extratropical systems were considered in this analysis, as defined by the National Hurricane Center (NHC) in the Hurricane Database (HURDAT). The rainfall dataset was divided into two subsets; one called Tropical Rainfall (TR) with the accumulated TC daily rainfall for each month and the other called Non-Tropical Rainfall (NTR) with the difference between TR and monthly precipitation, as performed by Cry (1967).

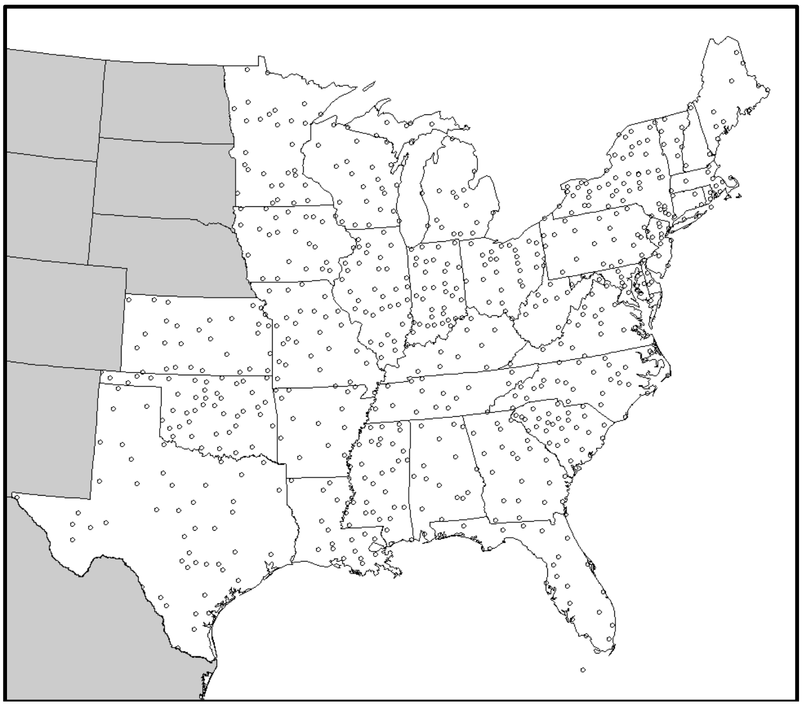


Figure 13: Study region and U.S. HCN stations.

The ENSO monthly SST anomalies used in this study were obtained from the Niño 3.4 region (5°N–5°S, 170°W–120°W) from the Climate Prediction Center (CPC), based on threshold of 0.3°C as suggested by Trenberth (1997). A more detailed description of the Niño 3.4 index can be found at http://www.cpc.ncep.noaa.gov/data/indices/. The ENSO index is identified using 6-month (June to November) averages of SST anomalies. El Nino was defined when the SST anomaly average was greater than 0.3°C and a La Niña when the SST anomaly average was at least 0.3°C below average. Figure 14 shows the ENSO 3.4 SST anomaly time series and the ENSO phases (cold, warm, and neutral).

AMO was named by Kerr (2000), and it is and index of North Atlantic sea surface temperatures between 0°-60° N latitude and 7.5° and 75° W longitude. The AMO phase impacts weather patterns such as rainfall and rivers flows over the continental U.S. (Enfield et al., 2001) and is linked to the Atlantic hurricane activity (Gray, 1990, Landsea et al., 1999, Goldenberg et al., 2001). The AMO dataset was obtained from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory/Physical Science Laboratory. The dataset can be downloaded from the NOAA web site (http://www.cdc.noaa.gov/Timeseries/AMO/). Note that AMO were averaged by the twelve months (January-December) anomalies values.

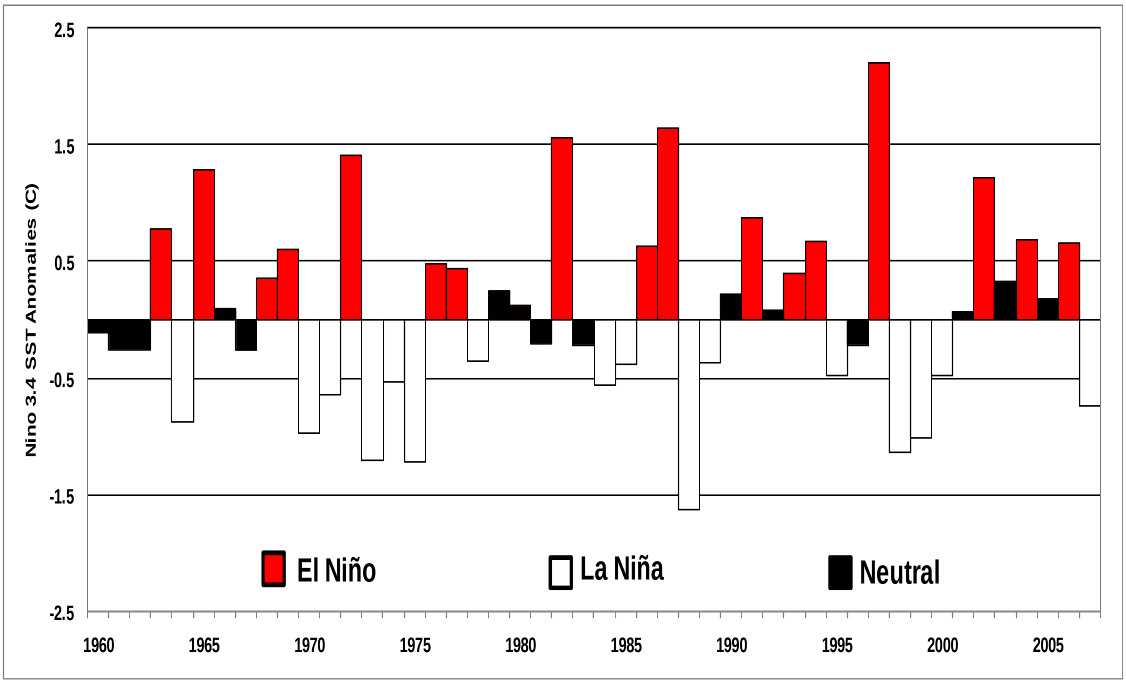


Figure 14: Pacific Nino 3-4 region SST anomalies and the JMA ENSO phases (Red for positive; white for negative; and black for neutral, based on 0.3°C thresholds.

METHODS

This study frames the definition of TC rainfall based on the general question:

what distance from the center of a TC can observed rainfall be accurately associated with that storm? Previous researchers investigated the swath of rain produced by a TC using different methods. Cry (1967) considered TC rainfall to be within the limits of the circulation ranging from under 100 kilometers to over 800 kilometers. Rao and Macarthur (1994) placed a grid over each storm and determined the rainfall within each grid cell. Gleason (2006) used a simple partition method to consider rainfall associated with TCs. His definition considered any rainfall within distances less than or equal to 600 km from the center of the storm as tropical cyclone rainfall. Separating rainfall into tropical and non-tropical cyclone components is a challenging task. TCs can produce rainfall for hundreds of kilometers from their centers (Larson, Zhou and Higgins 2005). Cerveny and Newman (2000) pointed out that there is a linear relationship between TC intensity and the amount of precipitation. However, there is no direct correlation between TC intensity, size, and strength.

Due to the asymmetrical structure and interactions with other weather systems, TC rainfall shields cannot be represented by a circle (Matyas 2007). However, in 90% of cases, TC's rainfall occurs within 600 km from the center (Englehart and Douglas, 2001). TC rainfall can be studied based on all rainfall data associated with the tropical storm, even after becoming extratropical or associating with a frontal system (Knight and Davis, 2007). However, this approach would overestimate the contribution of TC rainfall. This study used a radius of a 500 km (310 miles) centered on each storm track, based on the HURDAT dataset, to include the weather stations rain data; the TC precipitation was assumed to be symmetric around the storm center as noted by Larson, et al. (2005). The usual concept that a TC eye must move inland to affect a coastal area is inadequate and could be misleading regarding impacts of TC. In this study, any TC system within 500 km of the coast was included as a system capable of producing inland rainfall and therefore was defined as a landfalling storm. This criterion could be too large for some storms, but will only affect the number of storms and not the amount of rainfall. The 500-km criterion is an operational definition to reduce the influences of other meteorological systems. ArcMap 9.2 was used to plot and display all weather stations by year, subset those stations by the storms buffer region, and perform spatial analyses.

A simple Kriging quartile tool was used to create an interpolated TC rainfall surface (Chapman and Thornes 2003). Kriging is a stochastic technique, similar to Inverse Distance Weighting –IDW that use linear combinations of weight at unknown points to estimate values to unknown point. Anderson (2001) comparing three spatial interpolation methods of the air temperature data from the Phoenix Metropolitan area and found that Kriging produced the best estimation of the air temperature. Kriging has also been used effectively to interpolate rainfall data (Earls and Dixon, 2008, Miras-Avalos et al., 2007)

The Lambert Conic Equal Area projection was used to minimize errors in calculating TCs rainfall areas and volumes. The first step was selecting stations within 500 kilometers from the center of each storm position and computing the accumulated rainfall related to TC. The second step was interpolating the rainfall using simple Kriging, converting to a raster format, and clipping by the storm buffer area. The total rainfall volume for a given year was calculated in ArcMap as:

$$\{\boldsymbol{Volume = Pixel\ Average\ TC\ rainfall} \text{ x } \boldsymbol{Number\ of\ Pixels} \text{ x } \boldsymbol{Buffer\ Area}\ \}$$

The volume of rainfall was expressed in km^3.

Non-parametric Correlations

A correlation measures the linear relationship between variables (Field

2005). The most widely used method (for the complexity of their calculations, non-parametric were more complicated than linear correlations, it is not until recently that computers have overcome with this limitation) to evaluate linear correlations is the Pearson product moment correlation coefficient. Although a linear correlation coefficient can often give an approximate idea of the strength of the relation between the variables under study, it has a limited resistance and robustness, and lacks reliability in the determination of the level of significance (Haylock 2004). Rank (or Non-parametric) correlation coefficients can overcome these limitations; normally distributed data is also not a condition for these techniques.

Kendall's tau-b (τ) is a non-parametric correlation that measures the association of the number of concordant and discordant pairs of observations. A pair of values is said to be concordant if they vary together, and discordant if the vary differently. The coefficient ranges between -1 (ranks increasing separately) and +1 (ranks increasing together).

Teleconnections

TC rainfall is characterized by interannual and interdecadal variability. Those variations may be related to climate teleconnections such as El Niño Southern Oscillation and Atlantic Multidecadal Oscillation. In this paper, impacts of ENSO and AMO in the TC rainfall over United States are examined. Listed below are seven variables related with TC rainfalls chosen to test if there are any correlations with ENSO and AMO:

1) Month_tot - represents the total seasonal (June-November)rainfall (tropical and non-tropical);
2) TC_tot - total TC rainfall;
3) Non_tc tot- total rainfall produced by non-tropical systems;

4) Percentage_tc- percentage of TC rainfall of total rainfall;
5) Number of Storms – number of storms affecting the Eastern United States;
6) VOLUME - represents the total rainfall volume produced by TC;
7) AREA - the area affected by TC threshold.

- **ENSO**

Henderson-Sellers et al. (1998) pointed out that El Niño events are related to the seasonal frequency and interannual variations of tropical cyclone activity. Furthermore, several studies relate ENSO with tropical cyclone activity (Landsea et al. 1996, Bove et al. 1998, Landsea et al. 1999, Pielke and Landsea, 1999, Tonkin et al, 1997, Enfield et al. 2001, Walsh, 2004, Gray, 2006). Pielke and Landsea (1999) pointed out that during the cold phase ENSO (La Niña) events, the U.S. experiences a larger number of TCs and more damage compared to the warm ENSO (El Niño) phases.

- **AMO**

The Atlantic Multidecadal Oscillation (AMO) is defined by the SST between warm and cold phases within a 65-80 year cycle (Kerr, 2000). The AMO showed warm phases from 1860-1880 and 1940-1960 and cold phases from 1905-1925 and 1970-1994. A new AMO warm phase started circa 1995 (Enfield e tal.2001), and continued through the end of the study period, 2007. The relationship between TC and decadal-scale SSTs has been studied for decades.

RESULTS AND DISCUSSION

The study period showed an average of 313 stations (of the 717) affected by TC rainfall per year (Figure 15a), 1990 has lowest number of stations (52), and 1985 with the highest number of stations (936). The number of affected stations showed a slight positive trend, but was not statistically significant Instead, it shows a multidecadal oscillation; affected stations above average from the 1960s to mid 1970s and after the mid 1990s, and affected stations below average during late the 1970s, 1980s and early 1990s. The affected stations showed a high correlation with the AMO phase, significant at the 99% confidence level. The results of a *t-test* show that the affected stations are related to the AMO phase. The five-year moving average shows two periods with a lower number of stations affected by TC rainfall: 1971-1982 and 1987-1994, and a positive trend after 1995. The number of stations affected by TC rainfall per year is directly related to the number of storms and the travel time. However, averaging the stations affected by number of TC per year shows a different result (Figure 15b); annually variation but without any significant trend. This time series serves as an index of the annual average spatial extent of the storms that occurred each year. The greater the value, one can assume that the storms of that year affected larger areas then if this value is smaller. However, this is not an index for the number of storms or the total area of each year, but rather the average per storm. The average number of affected stations per storm shows less interannual variability when compared with the total number of affected stations per year. The average per storm decreases to 64 stations and the maximum number of stations occurred in 1979 with 121 stations. The five-year moving average shows an oscillation around the average.

The spatial distribution of annual average TC rainfall and the TC rainfall contributions in percent over the eastern and southern U.S. from 1960-2007 are shown in Figure 16. The TC average rainfall over the study period indicates that southern Florida receives over 14 cm, the highest amount of rainfall, on average in the eastern United States.

The coastal region extending from Southern Louisiana to South Virginia receives an average of 8-10 centimeters of TC rainfall; however, western Florida and

North Carolina's coasts receive an average of 12-14 cm of TC rainfall (Figure 3a). The amount of TC rainfall decreases rapidly towards the northwest. The region from western Texas, Oklahoma, and Kansas receive less than four centimeters of TC rainfall, on average. These results suggested that the TC rainfall contribution is directly related to the seasonal total rainfall, the storm path, storm intensity, and other factors such as ENSO and AMO phase could affect as well (Henderson-Sellers et al., 1998).

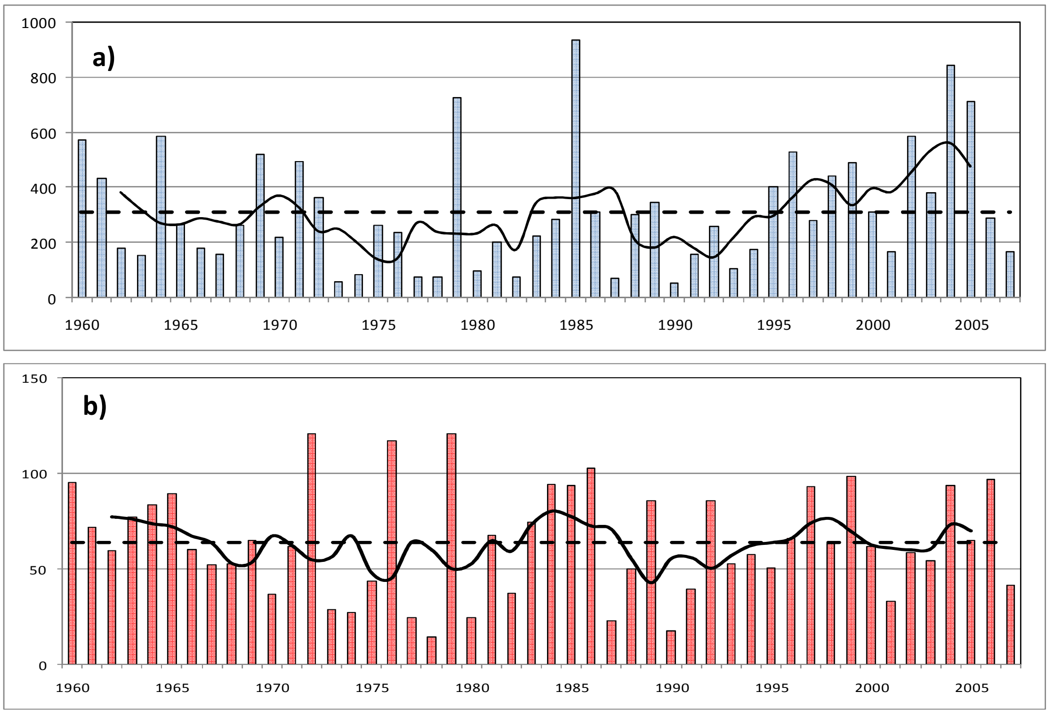


Figure 15: Number of TC affected stations by year in the Eastern United States. a) Total number of affected stations (bars), 48-year average (dashed line), and 5-year moving average (bold line); b) Total number of affected stations averaged by the number of storms per year (bars), 48-year average (dashed line), and the 5-year moving average (bold line).

The TC rainfall percentage is directly related with the total rainfall. TC contributes more than 14% in southern Texas and eastern North Carolina from June to November. However, Texas presents an average of 6-8 cm while North Carolina receives 10-12 cm. The coastal region from Texas to Maine receives more than 8% of TC rainfall. The TC rainfall contribution decreases northwestward as the total TC rainfall decrease.

Drier regions such as northern Texas, Oklahoma, and Kansas present a higher percentage of TC rainfall than the surrounded area, 8-10% of TC rainfall, due to fewer non-tropical systems (Figure 16b).

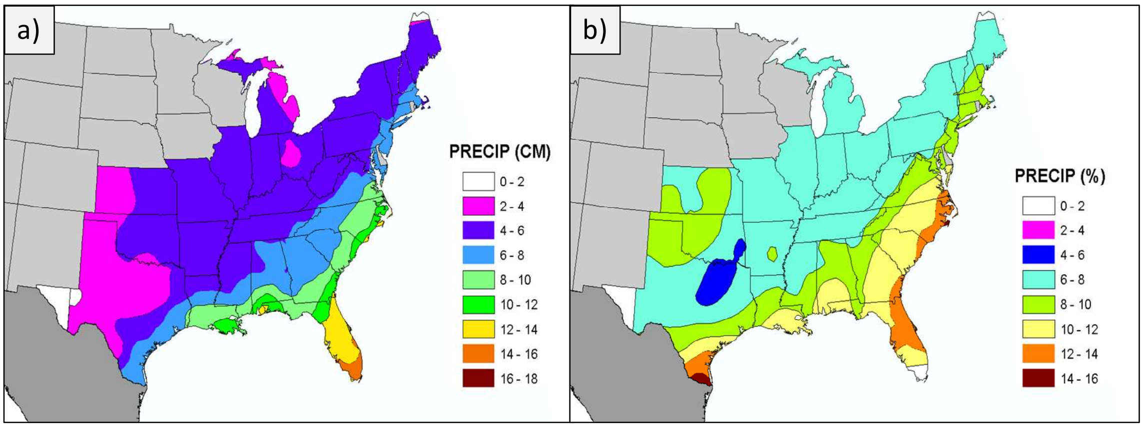


Figure 16: (a) Annual average of TC rainfall, and (b) TC rainfall contribution in percentage from June until November total rainfall (1960-2007).

Total rainfall (TC and non-TC rainfall) accumulates in all stations from June to November in the study period is shown in Figure 17a. Figure 17b represents the anomalies of the average normalized by the standard deviation during the study period, and overall, the total rainfall exhibit great yearly variation (2 ½ standard deviations). The time series presents a drier period in the first decade (1960-1970), and that is related to the positive phase of the Atlantic Multidecadal Oscillation (AMO), as described by Enfield, Mestas-Nunez and Trimble (2001). They found that AMO warm phase flattened the 500 Hpa geopotential height ridge-troughs in the northern tier, and has opposite effect in the southern tier over United States. The rainfall after 1970 was characterized by high interannual variability, and after 1990, a sequence of five years with values higher than average followed by five years with values lower than average. Total rainfall has a slight overall positive trend, and the Kendall's Tau B test indicates this trend is statistically significant (0.05 significance level), and similar to Karl and Knight (1998) and as described in the IPCC- Special Report Chapter 8-(1996).

TC rainfall accumulated by year is directly related to the number of storms (based on the 500 km threshold), the duration of each storm, and the storm velocity. TC rainfall time series present interannual variability (Figure 17c). TC rainfall anomalies of the average normalized by the standard deviation and the five year moving average are shown in Figure 17d. During the AMO (-), from the early 1970 until the middle 1990s, TC rainfall was predominantly below average; however, 1985 was the year with maximum SD (3.6). After 1995, TC rainfall was characterized by an above average period with the second maximum occurring in 2004. The moving average showed a positive trend after the middle 1990s, and the overall time series shows a slight positive trend; however, that was not statistically significant.

The TC rainfall contribution to the total rainfall presents a high yearly variation, from 2.5% in 1978 to 16% in 1985 (Figure 17e). The time series shows a negative trend during the first half of the study period (1960-1984) and a positive trend during the second half (1985-2007). Overall, the TC rainfall contribution has a slight positive trend; however, it is not statistically significant.

Figure 17 displays a time series of the anomaly of the annual TC rainfall average volume for United States and the five-year moving average. The time series shows an average of 107 km^3 and a positive rate of 1.5 km^3/yr. Kendall test results indicate that the trend is not statistically significant. The TC rainfall consists of interdecadal and interannual variations, also found by Ren et al. (2006). Figure 17a shows high yearly oscillation with a positive trend after 1990s. The volume distribution shows 16 years with values above average and 32 years with values below average, indicating a right skew to the distribution (Figure 17b). However, 65% of those years with positive values occurred after 1984, indicating that TCs are producing more volume of rainfall lately.

The maximum of 405.8 km^3 (3.6SD on Figure 17b) occurred in 1985 and the second highest value occurred in 2005 with 313.7 km^3 (2.6 SD on Figure 17b). The lowest TC volume occurred in 1978 with 8.9 km^3. The moving average followed the same positive trend as found in the total TC rainfall.

Comparing TC area (Figure 17c) with TC rainfall volume shows that there is no strong correlation. In some years, TCs travelled more distance covering a large area; however, they did not produce an equivalent amount of rain. The year 1979 is an example when TCs covered a large area with a corresponding small rainfall volume. After 1995, TCs are becoming more frequent, producing larger volume and affecting larger**.**

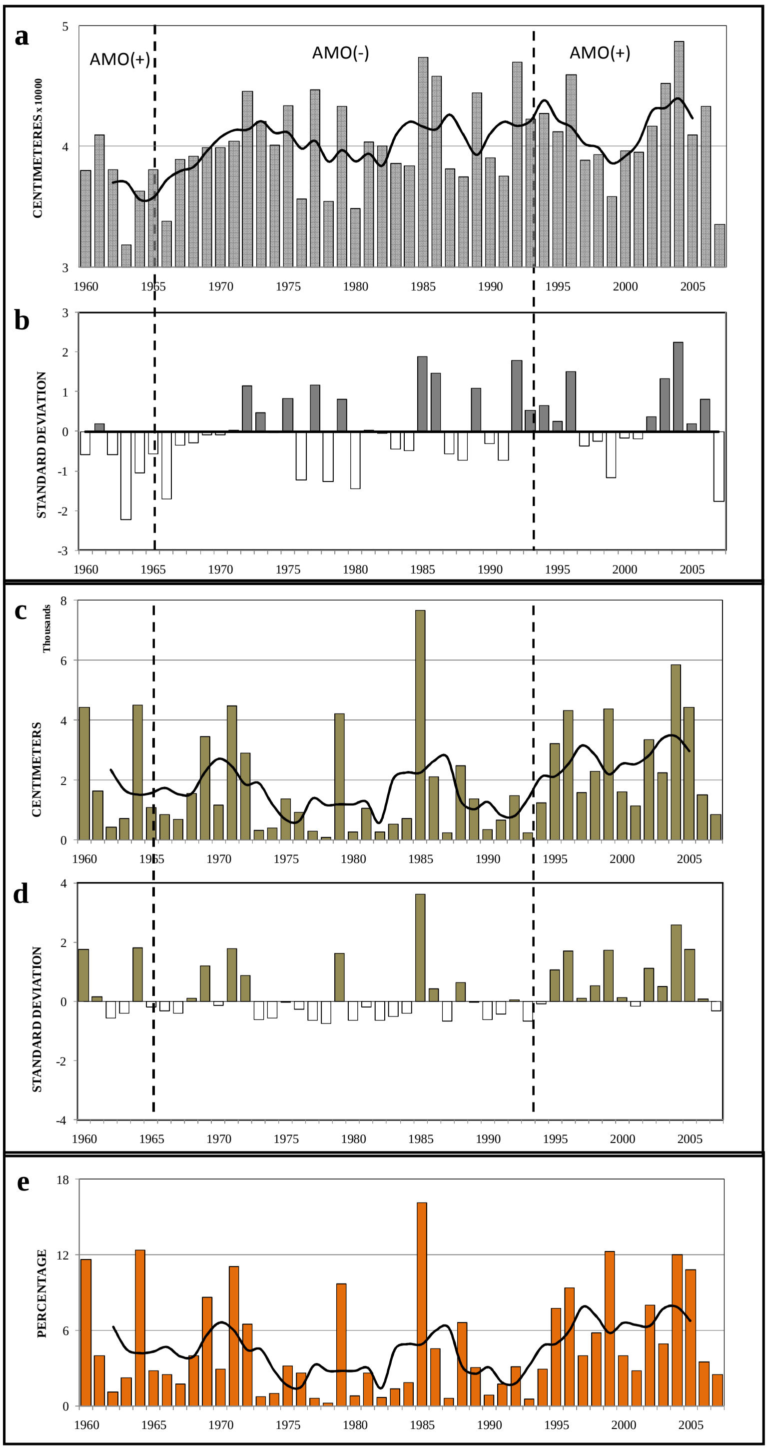
El Niño Southern Oscillation (ENSO)

Table 3 shows results of the *t-test* comparing ENSO phases, positive and negative, with TC variables. Results show that only Percentage_tc was statistically significant at the 95% confidence level, hence the null hypothesis of equal variance is rejected. However, the *t-test* for Percentage_tc under positive and negative ENSO conditions is insignificant. Finally, the 95% confident intervals include zero, indicating that the true difference between ENSO phases could be zero (right columns on Table 3). The variable Number of Storms shows the lowest significant value (Sig= 0.095), higher than 0.05, and the 95% confidence interval of the difference includes zero. Gray (1984) pointed out that differences in TC frequency between ENSO phases is related to the storm track, whereby during non-El Nino years, TC cross the Caribbean more frequently. In conclusion, there is no ENSO impact with the amount of TC rainfall over U.S.

Atlantic Multidecadal Oscillation – AMO

Wendland (1977, p.477) wrote, "Frequency and intensity of tropical storms are related to the magnitude and distribution of sea surface temperature (SST)." Recently,

Figure 17: Time series of seasonal (June to November) rainfall from 1960-2007, and AMO phases (dashed lines); (a) Total rainfall and total 5-year rainfall moving average (line); (b) Total rainfall anomalies from average (bars) (Average=40257 cm, SD= 3779cm); (c) TC rainfall accumulated by year (bars) and 5-year moving average (line); (d) TC rainfall anomaly accumulated by year (Average= 1931 cm, SD=1731 cm); (e) TC rainfall percentage of the total rainfall (bars), and 5-year moving average (line).



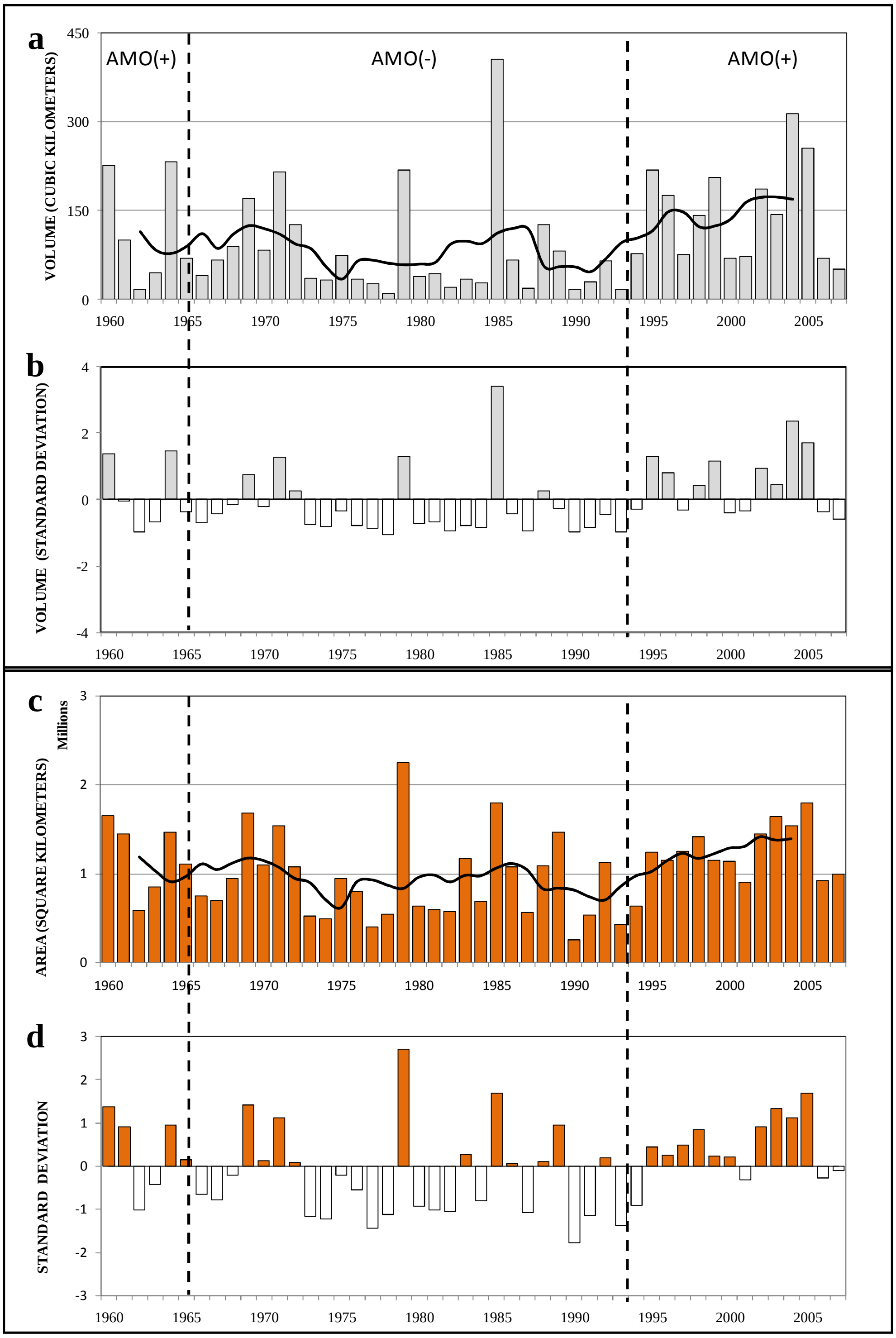


Figure 18: Volume and area of TC rainfall from 1960-2007. (a) TC rainfall volume (bars), and total 5-year rainfall moving average (bold line) (Average=103 km^3, SD= 89 km^3). (b) TC rainfall volume (bars). (c) Area of TC rainfall anomaly accumulated by year and 5-year moving average (Average= 10^6 km^2, SD=4.4 x10^5 km^2). (d) Area of TC rainfall anomalies accumulated by year.

Nyberg et al. (2007) found that the increase in hurricane activity since 1995 could be considered a return to normal TC activity when compared with other periods.

Table 2: *t-test* SPSS output comparing all variables with ENSO

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
								95% Confidence Interval of the Difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Month_tot	.671	.419	-1.001	32	.324	-524.9373	524.15231	-1592.60	542.72603
TC_tot	1.930	.174	1.036	32	.308	247.9443	239.32204	-239.539	735.42735
Non_tc tot	.077	.783	-1.620	32	.115	-772.8816	477.10139	-1744.71	198.94213
Percentage_tc	4.354	.045	1.287	32	.207	.0179	.01387	-.01040	.04612
VOLUME	2.840	.102	1.569	32	.126	49.9669	31.83848	-14.88601	114.81971
AREA	.222	.641	.925	32	.362	128453.54	138830.93	-154336	411242.9
Number of Storms	.499	.485	1.720	32	.095	1.3958	.81136	-.25684	3.04851

The AMO phases were tested against the suite of variables in Table 3. The Levene’s test for equality of variances shows that all probability of significance values is insignificant, hence the variances in warm and cold SST periods may be assumed equal. Levene's test (Levene 1960) is used to test if *k* samples have equal variances and no normal distribution. Equal variances across samples are called homogeneity of variance, and the Levene test can be used to verify that assumption**.** The next step using the *t-test* showed that Month_tot, TC_tot, VOLUME, and Percentage_tc presented values higher than 0.05, concluding at 95% confident intervals that the true difference between AMO phases could be zero. However, VOLUME has a close to significant value (0.054). Non-Tropical, AREA, and Number of Storms are found to have significantly different mean values between AMO phases at the 95% confident intervals. There are a significant differences in the values related to the AMO phase that cannot be attributed to variability alone. The North Atlantic SST works as fuel to power TC by providing moist enthalpy and instability (Elsner, 2006). That suggested the AMO positive phase could increase the seasonal number of storms, large area covered by those storms, and affecting the non-tropical rainfall. However, what is the relationship between AMO and TC rainfall variables? The Kendall test was used to determine the possible correlations.

The Kendall's Tau B (Table 5) test showed that AMO has a good correlation with almost all variables. *Month_tot* showed a negative correlation with AMO however, it was not statistically significant. *TC_tot, and Percentage_*tc showed a positive correlation with AMO, however they were not statistically significant at the 95% confidence level. The variables related to TC rainfall: *VOLUME, Number of Storms* and *AREA* have positive correlation with AMO at the 99% significance level.

In conclusion, ENSO and AMO phases play different roles in relation to TC rainfall contribution in the U.S. ENSO has a strong signal in relation to the number of storms, but there is not a statistically significant signal in the amount of TC rainfall. That is explained by the effect of ENSO positive phase in increasing the upper-atmosphere windshear over the Gulf region. On other hand, AMO presents a statistically significant level of correlation with all variables related to TC rainfall in the Eastern United States. Warmer SST is one of the factors to induce TC activity and frequency, resulting in increasing inland TC rainfall.

Table 3: *t-test* comparing all variables with AMO (+) with AMO (-)

Independent Samples Test

Equal variances assumed

	Levene's Test for Equality of Variances		t-test for Equality of Means						
								85% Confidence Interval of the Difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Month_tot	.099	.754	-1.498	46	.141	-643.9187	429.93880	-1273.34	-14.49660
TC_tot	.012	.914	1.350	46	.184	267.0116	197.83145	-22.60979	56.63308
Non_tc tot	.006	.939	-2.391	46	**.021**	-910.9304	381.05200	-1468.78	-353.078
Percentage_tc	.023	.880	1.630	46	.110	.0189	.01157	.00192	.03580
VOLUME	.560	.458	1.979	46	*.054*	51.1800	25.86421	13.31530	89.04472
AREA	.781	.381	2.181	46	**.034**	274762.50	125981.56	90327.93	459197.1
Number of Storms	1.268	.266	2.255	46	**.029**	1.5214	.67471	.53367	2.50919

SUMMARY

In this study, TC rainfall for 717 weather stations in the eastern United States, from 1960 until 2007, was studied comparing tropical-induced rainfall with major climate factors. The geographic distribution TC rainfall displays a pattern where coastal regions receive more TC rainfall when compared with inland regions. Florida and the North Carolina coast receive the highest values with an average of TC rainfall between 14 and 16 cm. However, TC rainfall shows a different pattern related to the overall rainfall contribution. TC rainfall in southern Texas and the North Carolina coast represents an average of 14-16% related to the total rainfall received in those regions between June and November.

TC rainfall shows high annual and multidecadal variability affecting the number of stations, the area covered by that rainfall, and the TC rainfall volume. However, the number of stations averaged by the number of storms per year showed highly annual variability with a slight negative trend. The total rainfall accumulated by year showed a dry period (1960s-1970s) followed by interannual oscillations between dry and wet periods. Overall, the total rainfall in the eastern U.S. exhibits a significant positive trend, which is in agreement with Karl and Knight (1998).

TC rainfall, during 1960-2007, presents high interannual variability and that is related to the frequency of tropical storms, intensity, and duration of those storms (number of storm days). The time series shows a significant (99% of significance) negative trend from the1960s until the middle of the 1980s and a positive trend (non-significant) from the middle of 1980 until 2007. TC frequency can be related to ENSO phases where the warm phase (El Niño) has a negative correlation. However, the cold and negative phases did not show any statistical correlation with TC frequency. On the other hand, AMO showed a strong correlation (95% significant level) with volume produced by TC rainfall and the number of storms. The AMO phases have a negative correlation with non-tropical rainfall and monthly rainfall however is not statistically significant at 95% confidence level.

Table 4: Kendall's Tau B test of correlation results: Correlations between AMO phase and all variables. Bold numbers represent statically significant correlations at 99% confidence level.

Correlations

			AMO (JAN_DEC)
Kendall's tau_b	**Month_tot**	Correlation Coefficient	-0.138
		Sig. (2-tailed)	0.166
	TC_tot	Correlation Coefficient	*0.186*
		Sig. (2-tailed)	*0.062*
	Non_tc tot	Correlation Coefficient	*-0.193*
		Sig. (2-tailed)	*0.053*
	Percentage_tc	Correlation Coefficient	*0.183*
		Sig. (2-tailed)	*0.067*
	Number of Storms	Correlation Coefficient	**.310(**)**
		Sig. (2-tailed)	**0.004**
	VOLUME	Correlation Coefficient	**.261(**)**
		Sig. (2-tailed)	**0.009**

* Correlation is significant at the .05 level (2-tailed).

** Correlation is significant at the .01 level (2-tailed).

IV VARIABILITY OF RAINFALL FROM TROPICAL CYCLONES IN EAST UNITED STATES AND ITS RELATION WITH AMO AND ENSO

INTRODUCTION

Tropical Cyclone (TC) is the generic term that includes tropical depressions, tropical storms, and hurricanes. They are one of the most powerful of nature’s phenomena and can produce catastrophic social, economic and ecological impacts. Over time the United States coastline is becoming more vulnerable to TC due to increasing population, beach erosion, and coastal subsidence (Blake et al. 2007). Extreme rainfall brings added hazards by producing flooding and mudslides, and compromises water quality (Cry, 1967). Emmanuel (2005, p191) pointed out “Some of the highest hurricane death tolls result from inland flooding….”A National Hurricane Center – NHC - study, from 1970 to 1999, showed that 59% of U.S. TC deaths were caused by freshwater flooding inland (Figure).

Rain associated with TCs can vary from a light drizzle to an extreme deluge (Glenson, 2006). Over a day or more, a single station can accumulate 50% to 100% of its mean annual precipitation (Simpson and Riehl, 1981, p. 17). TCs can produce rainfall for hundreds of kilometers from their storm centers and can propagate for hundreds of miles inland (Larson et al. 2005). TC rainfall resulting from storms with high wind speeds can also be misleading because much of the rain gets blown horizontally and does not enter the gauge properly (Emmanuel 2005, 182).

Tropical Cyclonic activity in the North Atlantic exhibits variability from interannual to interdecadal timescales (Landsea et al., 1999, Gray, 2006). TCs are affected by factors at different scales that affect the seasonality, number and intensity of

TC (Mo, 2000). For example, TC seasonality is associated with the seasonal cycle of SST with the tropical rainfall season extending from June-November (Cry, 1967), peaking in early September. During El Niño (ENSO positive - warm events), generally, there are twice as many storms as during La Nina (ENSO negative - cold phase) events (Bove, et al. 1998).

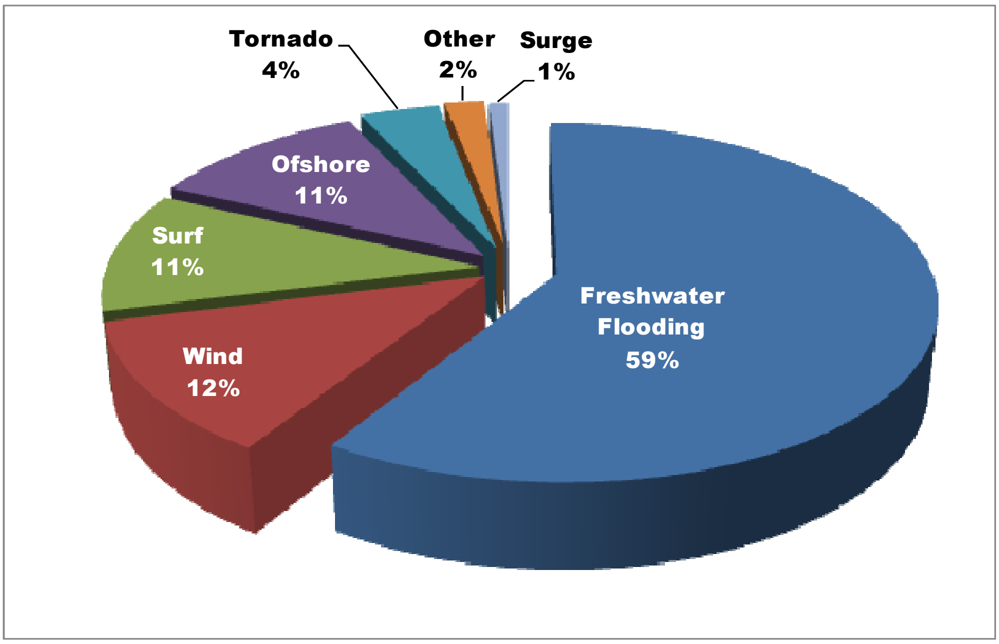


Figure 19 : Leading causes of TC deaths in the U.S. 1979-1999. Source NHC, 2007.

The ENSO positive phase causes an abnormally strong upper tropospheric westerly winds (easterly flow is more typical) over the equatorial West Atlantic and the Caribbean region (Gray 1984). That abnormal wind flow intensifies the wind shear over the TC formation region, affecting TC formation, intensity and path. However, TCs' genesis depends on other environmental factors such as the Coriolis parameter, low-level relative vorticity, weak vertical shear of horizontal winds, etc (Gray 2006).

The North Atlantic Basin also shows a multidecadal oscillation between cold and warm phases, known as the Atlantic Multidecadal Oscillation or AMO. Goldenberg et al. (2001) identify an AMO warm phase from 1944-1970 which had an average of 2.7

major hurricanes; this is higher than 1971-1994 AMO cold phase with an average of 1.5 major hurricanes. However, what is not known is how these indices affect tropical rainfall over Eastern U.S.

Over the 157 year HURDAT dataset (1851-2006), a typical season averages 8.7 tropical storms with 5.3 storms reaching hurricane strength (winds at least 33 ms^{-1}), and less than two becoming major hurricanes, Category 3, 4, and 5 on the Saffir-Simpson scale (Blake et al. 2007). TC damage is estimated based on the maximum wind speed and storm surge, but not on heavy rainfall, as defined by the Saffir-Simpson Hurricane Scale (SSHS) Table 1 (Simpson and Riehl 1981).

Table 5: Saffir-Simpson Hurricane Scale (SSHS), modified from Simpson and Riehl (1981)

Category	Winds (Mph)	Central Pressure (Millibars)	Surge (Feet)
1	74-95	> 979	4 to 5
2	96-110	965-979	6 to 8
3	111-130	945-964	9 to 12
4	131-155	920-944	13 to 18
5	> 155	< 920	> 18

The objectives of this paper are threefold:

1. Compare the number of TC days along the U.S. coast in two periods (1931-1960 and 1961-2007), and assess the influences of ENSO and AMO;
2. Analyze monthly and seasonal distribution of major storms (>=cat 3 on SSHS) by station and determine their geographical variability (1960-2007);

3. Analyze TC rainfall trends during the 1960-2007 periods and their correlation with ENSO and AMO.

DATA

Rainfall data were extracted from monthly rainfall observations from the United States Historical Climatology Network Monthly Precipitation and Temperature Data -USHCN from1960 to 2007(Williams, et al. 2007). This dataset contains 1221 high-quality stations from the U.S. Cooperative Observing Network within the 48 contiguous United States, and has undergone extensive quality assurance checks and includes only the most reliable and unbiased long-term records. Daily precipitation was updated for the same stations through the Southern Regional Climate Center (SRCC) Applied Climate Information System (ACIS). All weather stations were plotted by month and clipped by the storm's buffer region using ArcMap 9.2. Figure 20 provides an example of the clipped stations that feel under the 500 Km buffer for all storms during the study period. Resulting in 717 stations was selected from 34 states. However, despite the fact that the states of New Mexico, Colorado, and Nebraska were within the storm buffer, they were not included on this study because TC rainfall contribution are less than 1% of the total precipitation.

TC-related precipitation was considered as any precipitation produced by hurricanes and tropical storms with landfall or if the storms come within 500 km of shore. Tracks were included as long as the HURDAT dataset maintained it as "tropical," as many TC transform into extratropical systems makings landfall (Keim et al. 2004). Once a storm becomes extratropical, the dynamics within the storm changes, hence the rain produced is no longer considered "tropical". For that reason, tropical storms after becoming extratropical or subtropical systems were excluded from analysis.

Rainfall was divided into two subsets; one with the accumulated TC daily rainfall for each month called Tropical Rainfall (TR) and the other, the difference between TR and the monthly precipitation Non-Tropical Rainfall (NTR), as performed by (Cry 1967). As noted, once a storm becomes extratropical, it is classified as NTR. In addition, rainfall produced by subtropical storms is also classified as NTR.

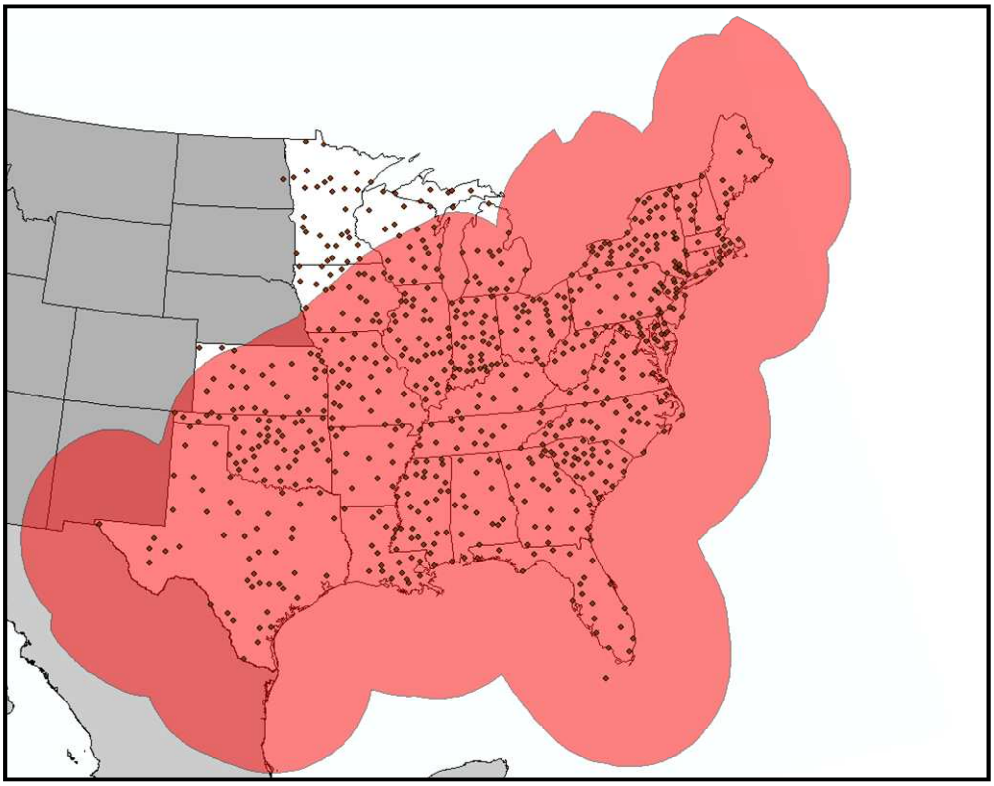


Figure 20 : Buffer of all storm 500 km from 1960-2007 (red area). Dark dots represent the 717 stations included in this study.

METHODS

Several studies used different methods to define the distance at which a TC could produce tropical rain from the storm center. Cry (1967) used surface weather maps and found that TC rainfall could extend over 800 km from the storm center. Recently Ren, et al. (2002) used a numerical technique based on the structure of the precipitation distribution to study the TC rainfall contribution in China. In this study, a TC center distance technique was used based on average TC size and the distance between rain bands from the station. Glenson (2006) used a simple partition method to consider rainfall associated with TCs, considering any rainfall within distances less than or equal to 600 km from the center of the storm as tropical cyclone rainfall. Knight and Davis (2007) based their study on all rainfall data associated with the tropical storm, even after becoming extratropical or associating with a frontal system. This approach could have overestimated the contribution of TC rainfall in the monthly totals.

Using guidance from these other papers, this paper considered all rain within 500 km from the center of the storms as that caused by the TC. The 500-km criterion is an operational definition to reduce the influences of other meteorological systems. TC landfall is defined as any TC center within 500 km from the coast. Figure 21 show examples of clipped stations under the 500 Km buffer, where Hurricane Camille in 1969 is shown with the area identified as under the influence of tropical rainfall, the USHCN stations within this area, and the storm classification (Saffir-Simpson).

RESULTS AND DISCUSSION

Storm Days

Storm days (SDs) were based on the hurricane day concept as defined by (Klotzbach and Gray 2008, p6): "A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds." SDs measures the number of the days of each TC center that either crossed, or came within 500 km of the coast of the United States (only Atlantic Basin storms). A SD could have at the same time one or more storms, but is its count as one SD. Figure 22 shows the number of SD by year whereby, the dashed red line represents the 5-year moving average. The moving average shows a negative trend from the 1960s to 1990s with a positive trend in 1970s, and a positive trend from 1990 to 2007. The years of 1933 and 2005, the most active years in the entire Atlantic Basin, showed the highest value during the study period 51 SDs and 43 SDs respectively, followed by 1936 and 1947 with 33 SDs each one. The period shows an average of 16.4 SDs per year. The first 30 years averaged 21 SDs, higher than the follow 48 years, with an average of just 14 SDs. The period from 1931 to 1960 represents the period examined by Cry (1967). Landsea et al. (1999) determined the period before 1944 as unreliable, whereby the data become more complete afterward due to use of reconnaissance aircraft. They pointed out that observation systems could bias the number of tropical cyclones (TCs).

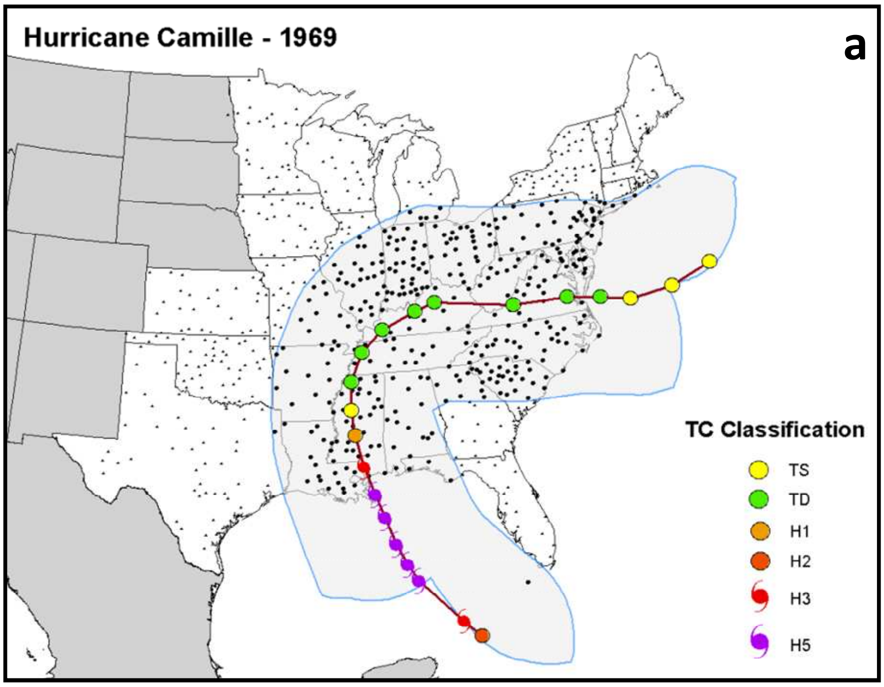


Figure 21: Hurricane Camille track (solid line) with the 500 Km buffer (shadow area). Dark dots represent the stations under the TC rain shadow, and the light dots represent stations in the study not affected by Camille.

Before 1940, primary surface stations and ships observed TCs. Reconnaissance aircraft then collected data beginning in the mid-40s. After the 1960s, meteorological satellites were used to observe TCs (Henderson-Sellers, et al. 1998, Landsea, et al. 1999). The changes in observational platforms might explain part of the variations in the number of SDs between periods. However, Landsea (2007) argues that the number of TC before 1944 could have some differences in the open Atlantic region, though these differences are probably minimal for landfalling storms. The 30-year period (1931-1960) presents a closer number of SD compared with the 47-year period (1961-2007), 619 SDs and 642 SDs respectively.

Figure 23 compare the monthly averages of the total SDs between 1931-1960 and 1961-2007 periods. The first period presents higher average monthly SDs than the second period; August has the highest difference of 2.4 SDs on average. These results indicate that the period of 1931-1960 had relatively more storms making landfall or coming within 500 km of the U.S. coast than 1961-2007.

The SDs difference between periods can be explained by the ENSO and AMO phases combined. Figure 24 shows the SDs departure from the overall average, the phase, ENSO (+) events, and AMO. During all 1931-1960 period, AMO was in the positive phase and had three ENSO (+) events. SD showed no great difference between positive and negative anomalies; however, the positive cases presented higher values compared to the negative anomalies. After 1964, AMO started the cold phase until 1993, when it returned to the warm phase. This latter period was characterized by 12 ENSO (+) phase years, where 1982-1983 is considered the strongest ever registered, followed by the second strongest event in 1997-1998. The combination of AMO and ENSO conditions caused the number of positive SD anomalies to be almost half of the negative SD anomalies, which explained why 1931-1960 showed more SD than 1961-2007.

To understand daily variations of SDs in both periods we accumulated SDs by day, from 1931-1960 and from1961-2007, with results shown in Figure 25 for the duration of hurricane season (June 1 to November 30).

- **1931-1960**

The number of SDs in June is characterized by a bi-modal cycle. One maximum occurred on the first half of the moth and a second one on the end of the month. Overall, June showed higher values of SDs on the first period compared with the second one. July also presents a bi-modal frequency of SDs in Figure 25a, with a positive trend toward the end of the month. August showed lower values on the fifth with three SDs, and the highest overall value at 12 SD on the 29th. September presents high values at the

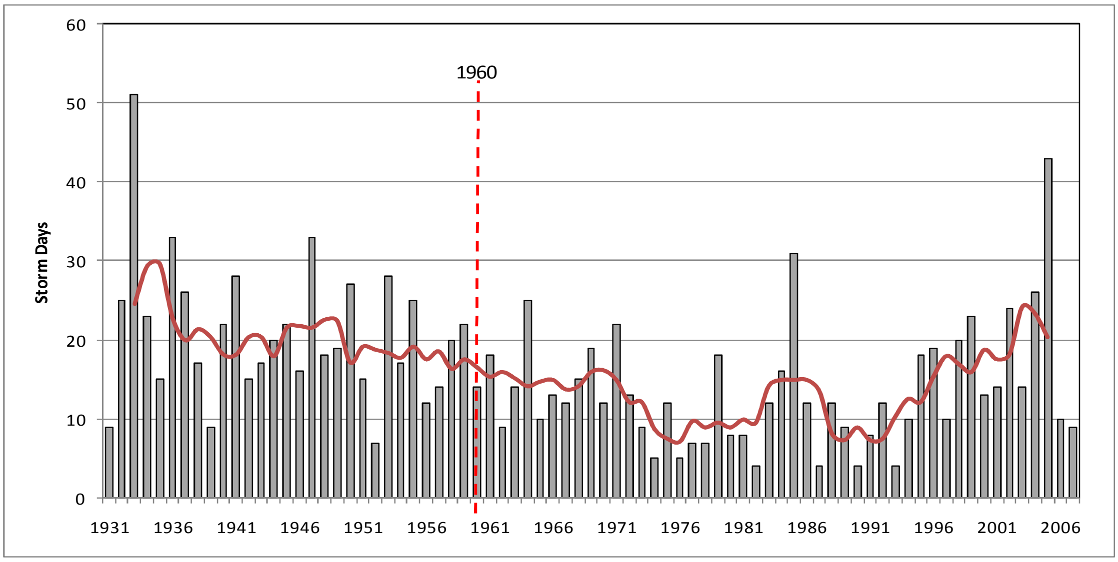


Figure 22: Storm days from 1931 to 2007, 5-year moving average (bold line), and dashed line marking the year of 1960, that represents the end of Cry (1967) study period.

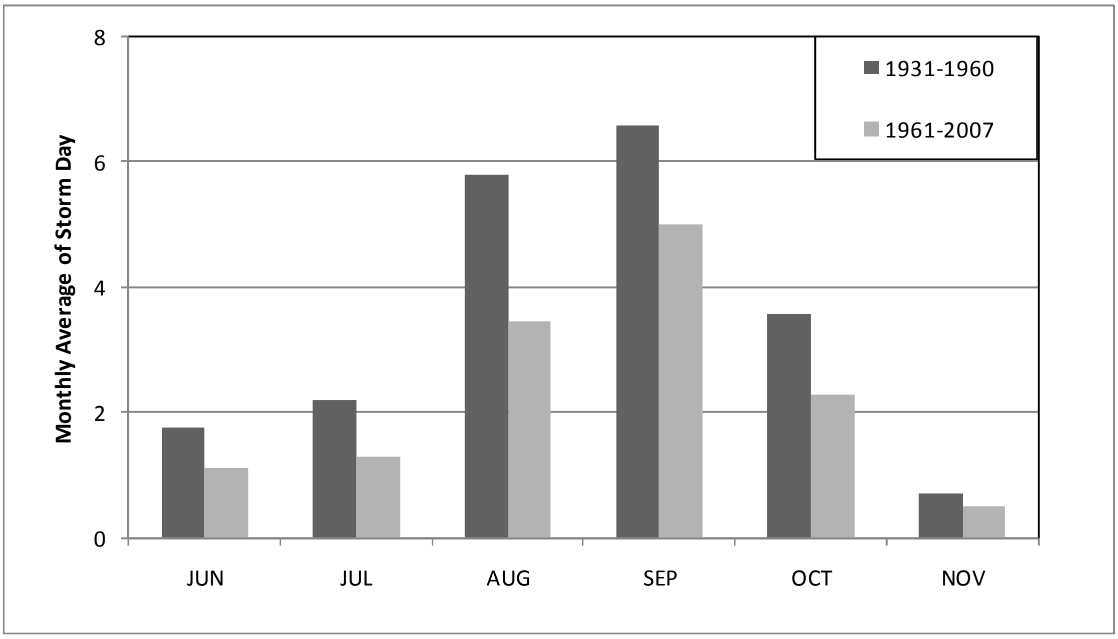


Figure 23: Monthly storms days from 1931-1960 and 1961-2007.

beginning and the end of the month. October shows another bi-modal cycle with two maxima, one on day 4 and other on day 12.

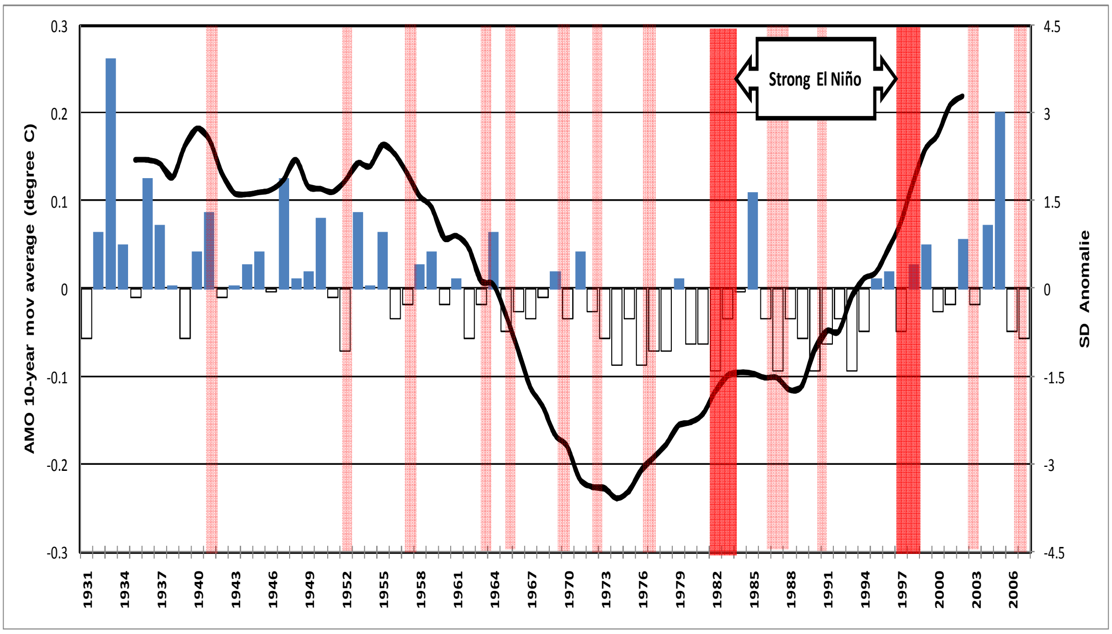


Figure 24: SD anomalies from 1931-2007 (blue bars positive values, and with bars negative values), AMO 10-year moving average (line), and ENSO (+) phase (red bars). The dark red bars represent the strongest ENSO (+) events.

At the end of the season, fewer storms get close to the U.S. coast. This period shows November with more storms at the beginning of the month. The period from June 1 to November 30 has 32 days with zero SDs, and that represents 17.7% of the total number of days.

- **1960-2007**

SDs in June is characterized by two periods of TC activity, one more number of SD in the first half of the month and the second at the last half of the month (Figure 24b). July presents more SDs compared with the previous month with a slight positive trend towards to the end of month.

August presents three maximum values (11 SDS) in Figure 25b, August 16, 28th and 31st respectively. This month is characterized by periods of high TC activity with less activity, and with a positive trend towards to the end of month. On Figure 25b, September has the highest overall value for a single day 16 SDs on the 11th and a significant decrease of the number of SDs after that. In general, October presents a negative trend from the beginning to the end of the month with the maximum values occurring in the middle of the month. November show two periods with SDS; one at the beginning of the month ad a second at the middle of the month

Overall, both periods showed an increase of SDs from June to September and a decrease from September to November, however, the first period showed more variation between higher and lower values, a rollercoaster shape. The second period, from 1961 to 2007 showed fewer SDs at the beginning and the end of the season, but with higher values occurring on September while the first period showed the higher value of SDs in August.

SDs is affected by the number of storms and duration of each one. In order to compare the two study periods, each day of the first period was divided by 30 and the second period by 47, then the second period was subtract by the first period (Figure 26). Overall, the averaged SDs difference showed that the first period had more days with SD occurrences compared with the second period. September 9 to 11th showed highest difference in SD in 1961-2007 compared with 1931-1960. Another relevant fact is that during 1931-1960, November had more SD on the first half of the month and, 1961-2007 presented more SD in the second half.

Spatial and Temporal Variation of Major Storms

Major tropical storms (MS, category 3-5) are classified at the Saffir-Simpson Hurricane Scale (SSHS) as storms with sustained winds equals or higher than 114 kt.

These storms often have storm surges of three meters or more (Blake et al. 2007). Figure 27 shows the monthly frequency of major storms on the United States Atlantic coast from 1960-2007. The percentage represents the frequency of each station was within 500 km from the center of a major tropical storm in relation of the total major storms. MS affect only the Florida coastal stations during June; July has also a frequency of 2-5%, though the area affected is larger and is concentrated along the Gulf Coast totaling only 2-5%. However, during July, those storms travel further inland, affecting stations in north Mississippi and Alabama. August presented a considerable increase in the number of stations and the frequency of MS. Texas, Louisiana, south Florida, and North Carolina show a frequency of MS from 8-10%. The storm path during this month split geographically: to the west from Alabama to Texas, along the East Coast from South Carolina to New Jersey, leaving Georgia with only few stations impacted by MS rainfall which an area with very few landfalls (Keim et al. 2006). September has the highest number of stations and the highest frequency of MS.

This month presents MS more frequently along the Gulf of Mexico, including Louisiana, Mississippi, and west Florida with 19-21% of all MS. The region from Virginia to Maine is not much affected by MS, showing a lower frequency of 2-5% only. During October, MS show a higher frequency in Louisiana, Mississippi and south Alabama, 6-7%. November shows a pattern similar to June and July, stations from eastern Florida to south Louisiana receive 2-5% of MS.

Seasonally, from June to November, MS presents a higher frequency of storms in the Gulf of Mexico coast stations, decreasing rapidly inland and northeastward (Figure 27). During the period of 1960-2007 stations in western Florida, south Louisiana,

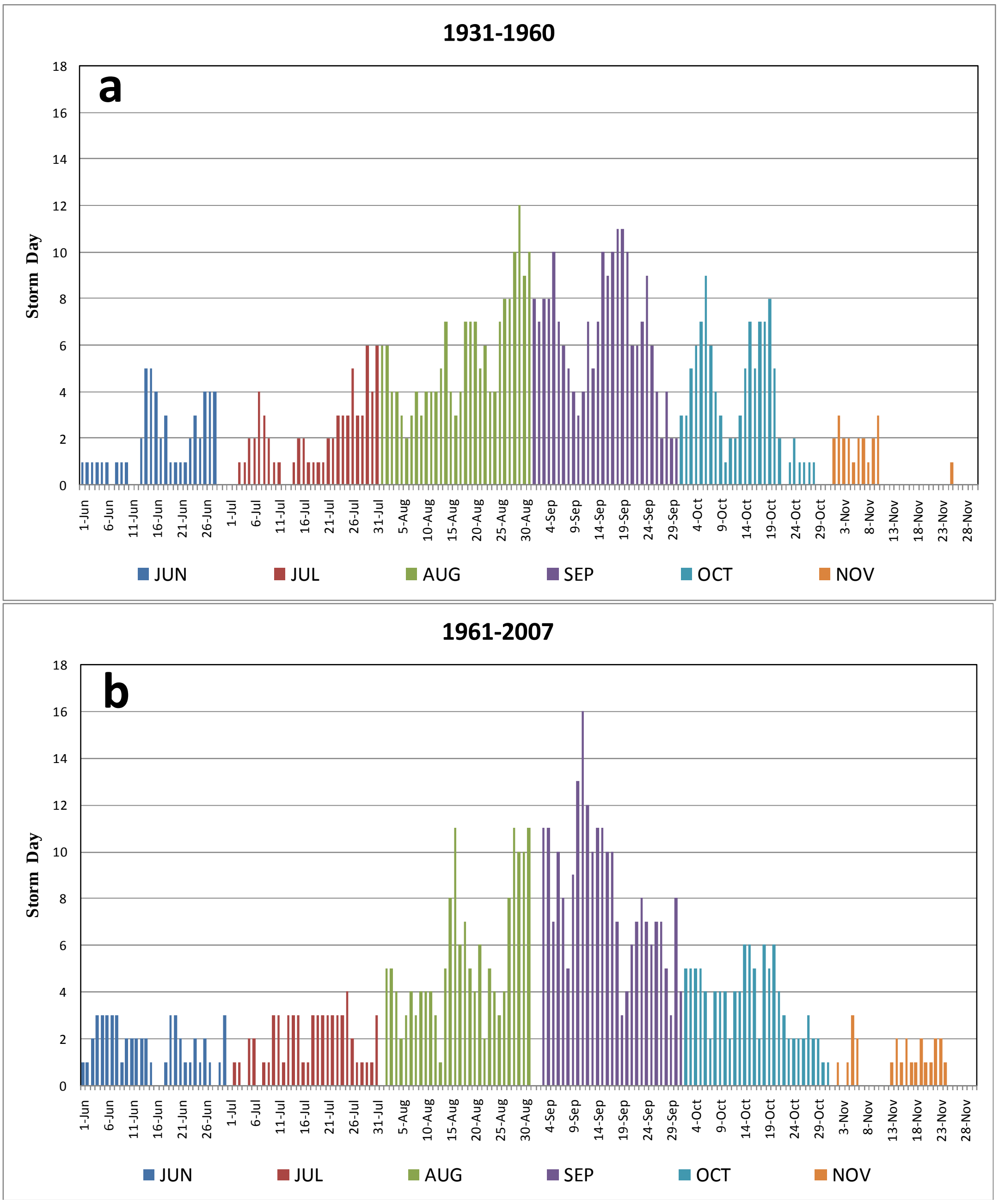


Figure 25: Storm Days (SDs) accumulated daily, (a) 1931-1960; (b) from 1961-2007during the storm season (June –November).

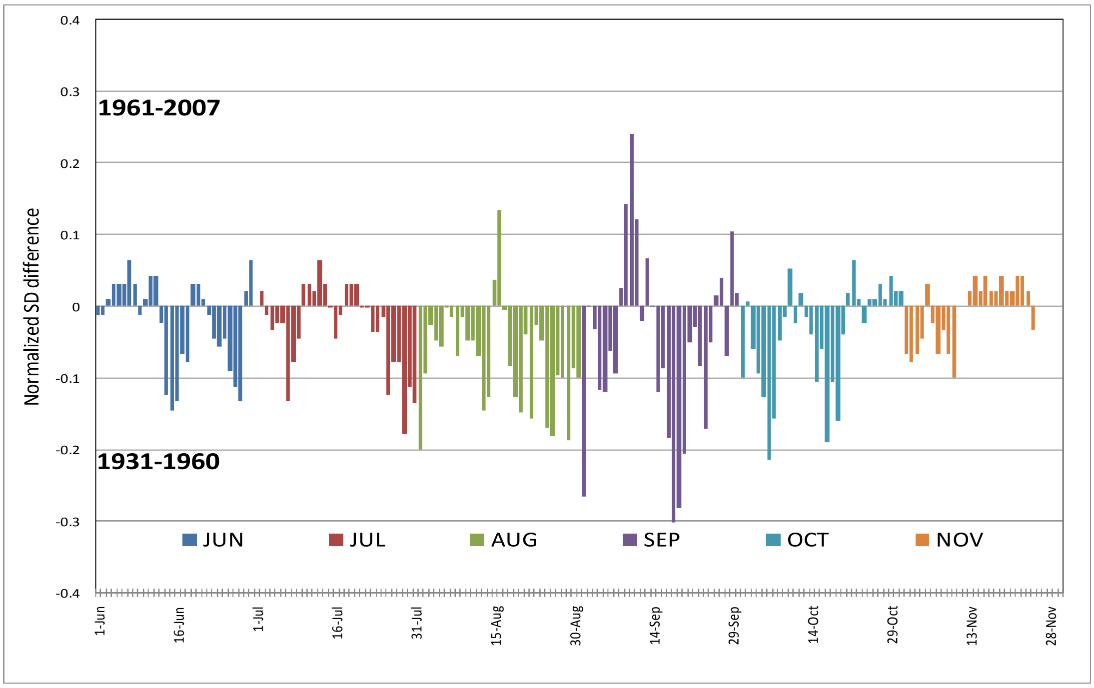


Figure 26: Normalized SDs difference between 1931-1960 and 1961-2007 periods (Average from 1931-1960 minus average from 1961-2007).

south Mississippi and Alabama received 26-38% of MS. In Texas, south stations showed a higher frequency of MS than other stations within the state at 22-25% of MS. The coast of North Carolina has enhanced frequency of MS than the surrounding region at 22-25%. It is well known that MS do not generally travel further north, as they lose their main energy source in that region; warm water. However, some MSs reach latitudes north of 40° North during the season. Coastal stations north of Virginia receive at most 7% of MS. As shown in

Figure **28**, the Gulf region demonstrates higher frequencies of MS than other U.S. region. Nevertheless, what does this mean in term of risk? This question can be answered by the MS anomaly for each station. The MS anomaly was calculated by subtracting the accumulated number of MS during 1960-2007 for each station from the total average of MS, and dividing by the overall standard deviation of MS. Simple Kriging was used to interpolate the results and create the MS anomaly surface (Figure 29). The results show that region from Florida to North Carolina, and south Louisiana presented more than two standard deviations of MS. The MS anomaly surface shows a second region with high risk of MS, from Texas to Massachusetts, with 1-2 standard deviations. Florida and Louisiana are more affected by MS than other regions and note that the number of SD has been increasing since 1990. However, are those TC producing more rainfall over U.S. and what is the contribution of major climate factor such as ENSO and AMO are related with that rainfall? The next two topics will address those questions.

TC Rainfall Trend

The temporal trends of tropical cyclone rainfall were examined during the hurricane season (June-November; Figure 30). Globally, precipitation over land has increased during the twentieth century (New, et al. 2001). More specifically, Knight and Davis (2007) found an increase in TC rainfall from 1980 to 2004. However, that increase in TC rainfall can be related to an increase in TC activity from 1995 to 2000. To filter the multidecadal oscillation, a long period was used on this study, from 1960-2007. The Kendall Tau-B test indicates that only 30 of 717 stations have a positive trend ($\alpha=0.05$) and 10 stations showed a negative trend at the same significance level. There are four distinct regions with an increase in TC rainfall: 1) Virginia, Maryland and Delaware, 2) Florida, Georgia, Alabama, Mississippi, and Louisiana, 3) south Texas, and 4) New England. These results showed some significant differences with Curtis (2007) findings. He founded that central Georgia showed a positive trend in the rainfall mean (tropical and non-tropical) and this study found mixed trends in TC rainfall. Another difference occurred in Florida and the Northeast U.S., where this study founded a positive trend in TC rainfall while Curtis (2007) showed no significant trend in mean and extreme values in those regions. However, Curtis (2007) did not separate TC from Non-TC rainfall; he assumed the most precipitation from August to October is produced by tropical systems, and that could be the reason of those differences. However, he found an increase in extreme rainfall events in Louisiana, Mississippi, and Alabama, and that can be attributed to TC rainfall, similar to that shown in Figure 30.

This pattern suggested that TCs are producing more rainfall at Gulf coast stations as result of the increase of TC activity/intensity in recent years. In the Mid-Atlantic region, the positive and negative trends could be related to not only storm tracks and intensity, but also by regional geographic features.

TC Rainfall and Teleconnections

TC rainfall is characterized by interannual and interdecadal variability. Those variations can be related to climate teleconnections such as ENSO and AMO (Landsea, et al. 1999, Gray 2006). Various studies investigated the potential effect of long-term global warming in the Atlantic SST and the correlations with the number and strength of TC. TC seasonality associated with the maximum SST peaks during the late summer.

Tonkin et al. (1997) argued the importance of a SST greater than 26ºC threshold in TC formation and concluded no clear trends in TC intensity above 28ºC were evident. Landsea et al. (1999) point out that the discrepancy between interannual and interdecadal TC activity with the SST in the North Atlantic Basin may be explained by the interactions of the SSTs with other environmental controls such as El Niño Southern Oscillation (ENSO). However, ENSO has influence on TC activity by an anomalous increase in upper tropospheric westerly winds over the Caribbean basin and the equatorial Atlantic (Gray 1984). Those anomalous winds, as described by Gray, increase the tropospheric vertical wind shear creating an unfavorable environment for TC development and maintenance. Are the AMO and ENSO teleconnections related to TC rainfall in the east United States? To answer this question, a Kendall Tau-B test was used to correlate TC rainfall with AMO and ENSO phases during the period of 1960-2007. Results showed three distinct regions with high positive correlation between annual TC rainfall and AMO (+) phase (Figure 31): one from Georgia to Maine and other in Texas with a positive correlation with the AMO (+).This spatial pattern is roughly consistent with Curtis (2007). That suggests stations along the U.S. east coast have been more affected by TC rainfall during AMO (+) than stations on the Gulf Coast. From Florida to Louisiana there was no association found with AMO, even though that region was affected by MS during the study period, only one station in Louisiana and one in north Mississippi presented a positive correlation with AMO.

However, Curtis (2007) showed a positive correlation with AMO (+) in Florida while this study found no correlation with TC rainfall and AMO. That suggests the non-TC rainfall may be related to AMO (+) in south Florida. Comparison between Figure 29 (TC rainfall trend) and Figure 30 (AMO correlation showed a similar pattern. That suggested an increase in TC rainfall is correlated to the AMO positive phase.

On other hand, ENSO presented a different TC rainfall impact. Texas has the majority of stations with some correlation between TC rainfall and ENSO. Only one station in Pennsylvania is correlated with El Niño at 95% confidence level (Figure 32**).** El Niño showed a negative correlation with TC rainfall and positive correlation with La Niña at the 95% of confidence level.

SUMMARY

In this study, TC rainfall of 717 weather stations in eastern United States from 1960-2007 from U.S. Historical Climatology Network (USHCN) were analyzed with a special focus on the long term trends and correlations with major climate events (AMO and ENSO). Rainfall was considered as tropical based on a circle of 500 km from the center of each storm. Storms tracks based on the HURDAT dataset from 1931-2007 was used to compare the number of accumulated storm days in that period.

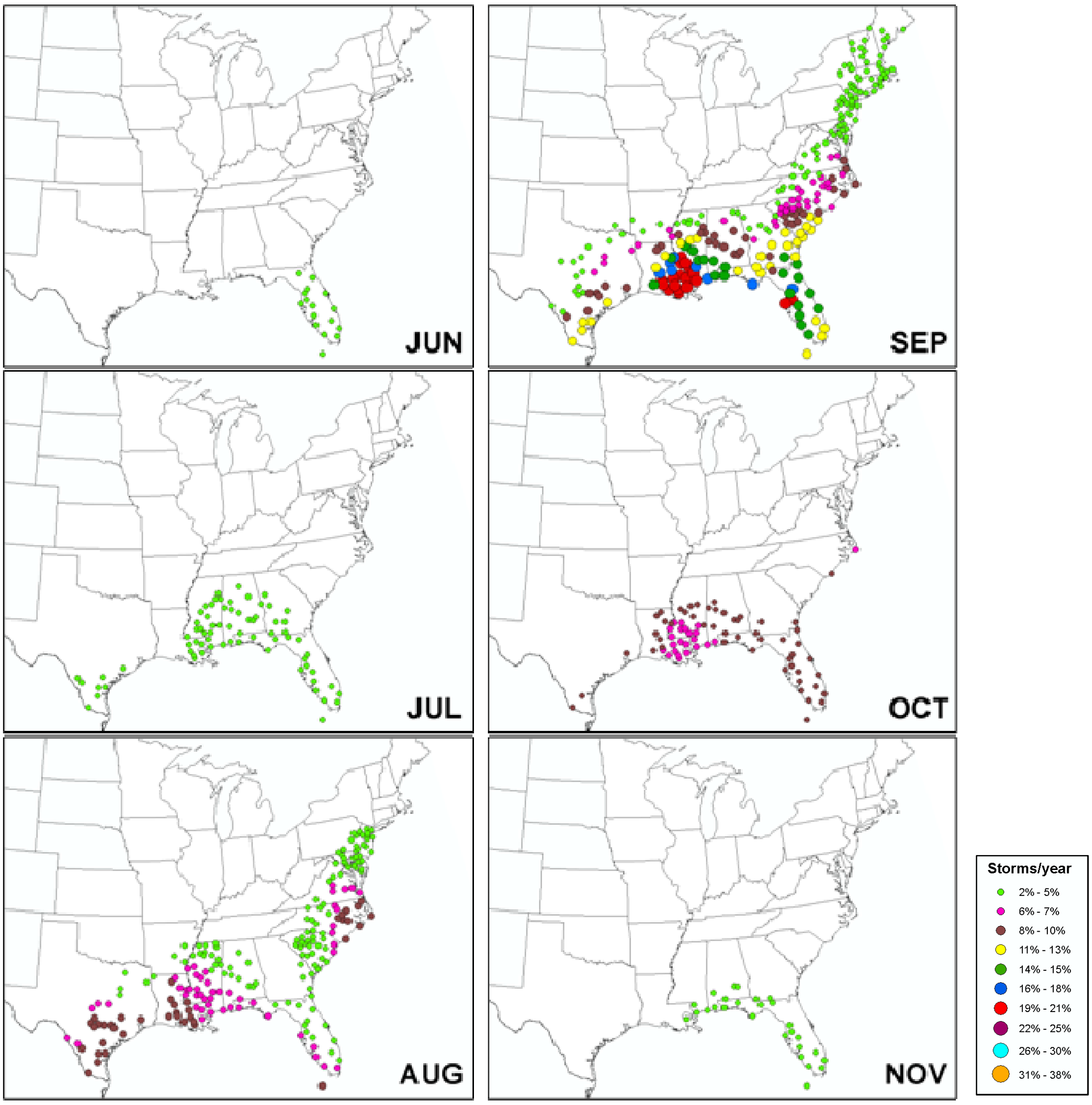


Figure 27: Major Storm frequencies spatial distribution from June to November during the study period of 1960-2007.

Only hurricanes and tropical storms were considered on this study. Once a storm becomes extratropical, the dynamics within the storm changes, hence the rain produced is no longer considered “tropical”. For that reason, tropical storms after becoming extratropical or subtropical systems were excluded from analysis. TC was considered “landfalling” storm when it is center came within 500 km of the U.S. coast, landfalling storm, creating Storm Day (SD) value. A SD could have one or more storms at the same time within the study region.

Tropical storm data and counts before 1960 are considered unreliable, as pointed out by Landsea et al. (2007). He argues that before the reconnaissance aircraft in 1944 some storms could be not accounted for. However, with the landfall 500 km criteria, there is a great chance that these storms would be account on this study. The period of 1931-1960 showed a higher number of SDs compared to 1961-2007. A positive AMO phase and few ENSO (+) events combined to allow more storms to the affect U.S. coast. During the AMO (-) phase (1960s to 1990s) most of the years have SDs below average, and after 1990s, with the return of the AMO (+), SDs become positive again.

SDs accumulated by day during 1931-1960 and 1961-2007 showed different patterns. The first period was characterized by having August with the maximum SD and September and October with a bimodal distribution. The second period showed August with a bimodal phase and September with the highest number of SD.

There is a clear shift in the SDs between those periods, with more SDs from 1931-1960 during the beginning of the season (June) and in the middle of the season (September), whereby they account later in the season from 1961-2007. This concept was applied to count how many days the study region had major storms, as defined by SSHS, have winds equal to or higher than 111mph and can produce extensive damage on coastal regions (Blake et al. 2007). Black et al. (2007) founded that between 1966 and 2006 major storms had an average of 2.3 storms per year. Major storms recorded during the 1960-2007 period shows a geographical shift during the hurricane season. They affect Gulf Coast stations at the beginning of the season (June and July), expanding to the U.S.

east coast in August and September, and returning to the Gulf in October and November. Overall, east Florida, Louisiana, Mississippi, and south Alabama receives the highest frequency of MS during the study period (31 -38% of all storms).MS frequency decrease towards inland and over the NE U.S. coast, with less than 7% of total storms based on the 500 km criteria. The spatial distribution of the MS anomalies shows two regions with high frequency of MS during the study period (two standard deviation or higher): South Louisiana and from Florida to coastal North Carolina. Many studies show that inland rainfall has an increase during the last century. However, some regions showed negative trends as pointed out by New et al. (2001). They pointed out that ENSO represents the dominant global and hemispheric variability, with strong signals in the tropics and extra-tropics, with strong influence over the southern and Midwest United States; This study separated TC rainfall from the non-tropical rainfall, and founded that several stations in the Gulf of Mexico and in the NE United States showed a positive annual trend (95% confident level). The first region is similar to the extreme precipitation region as founded by Curtis (2008); however, he

TC rainfall was tested with AMO and ENSO phases. Our results showed that AMO (+) has a strong positive correlation (95% confident level) with TC rainfall over the United States east coast and in south Texas. This result, in general, is similar to Curtis' (2008) findings. Nevertheless, there are some significant differences with Curtis (2007) findings. He founded that central Georgia showed a positive trend in the rainfall mean (tropical and non-tropical) and this study found mixed trends in TC rainfall. Another difference occurred in Florida and the Northeast U.S., where this study founded a positive trend in TC rainfall while Curtis (2007) showed no significant trend in mean and extreme values in those regions.

Finally, associations were tested between TC rainfall and ENSO phases. Results showed that only Texas stations had strong correlations with ENSO phases. ENSO (+) -El Niño - contributes negatively to the Texas TC rainfall and ENSO (-) -La Niña - contributes positively. In conclusion, an increase in TC rainfall over the region from Louisiana to Florida can be linked to the frequency of MS during the study region with no correlation with AMO or ENSO.

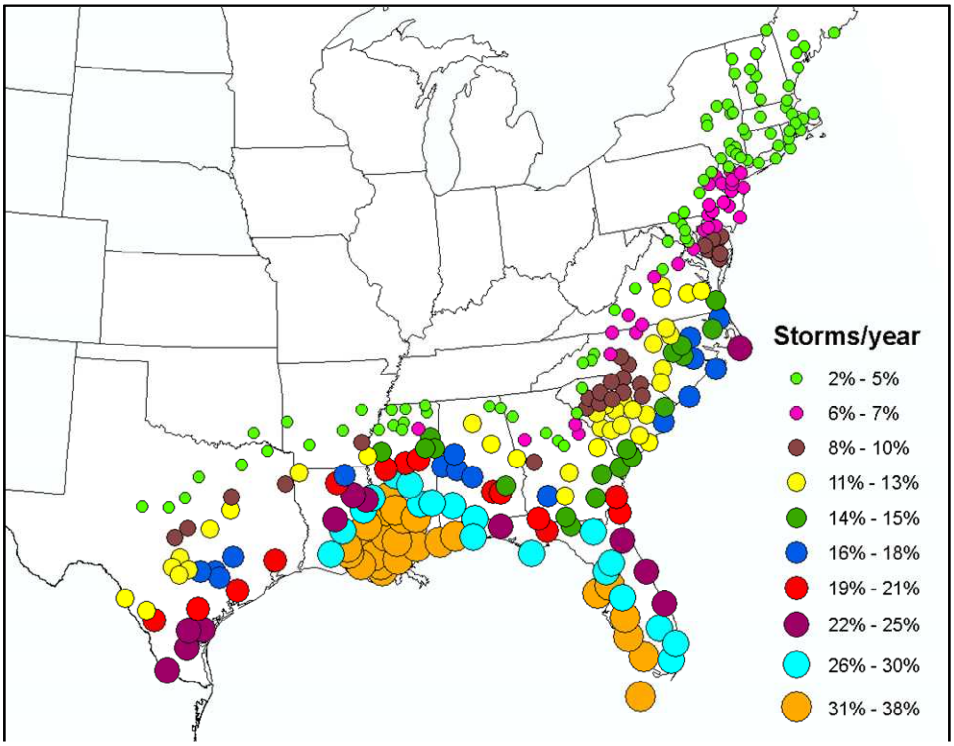


Figure 28: Seasonal frequency of major storms (1960 to 2007) by weather stations.

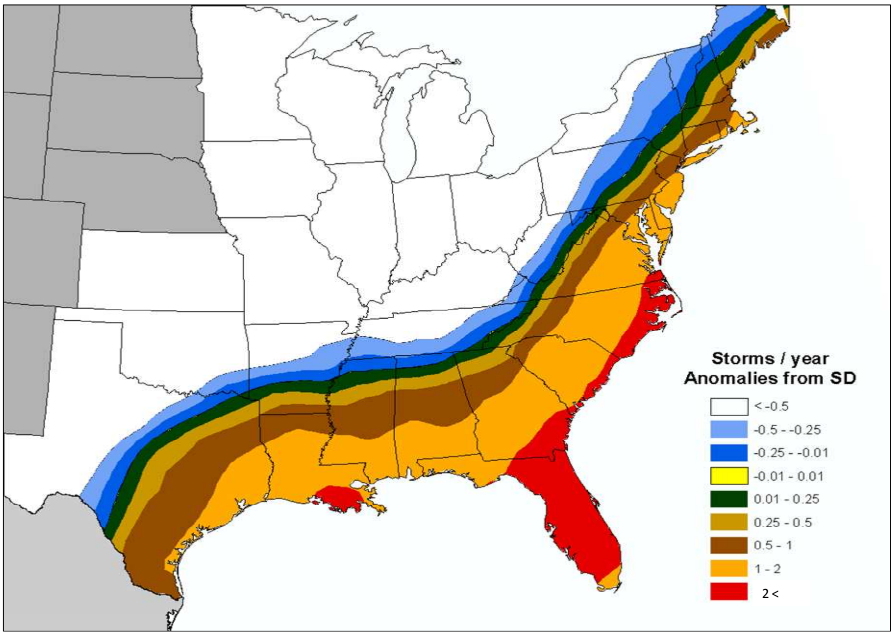


Figure 29: Spatial distribution of the major storms anomalies during the period of 1960 to 2007. The red region represents the area with the highest frequency of MS compared with

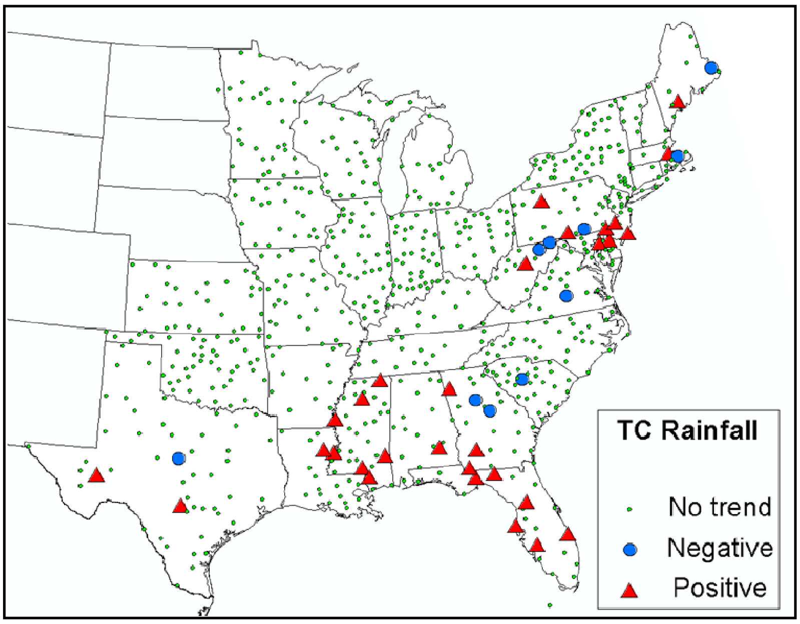


Figure 30**:** Yearly change in TC rainfall at each station from 1960-2007. Red triangle represents stations where the trend is positive and significant at α=0.05. Blue circles indicate stations with a decrease in TC rainfall significant at α=0.05. Dotted points represent stations with no significant trend.

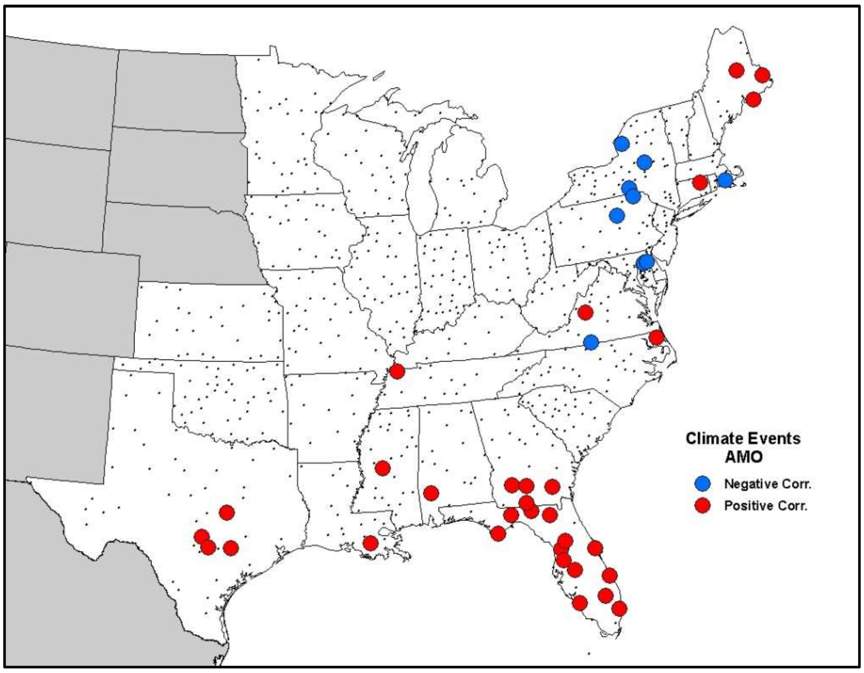


Figure 31: Correlation (95% of confident level) between TC rainfall and AMO. Red circles represent a positive correlation with AMO blue circles negative correlation with AMO.

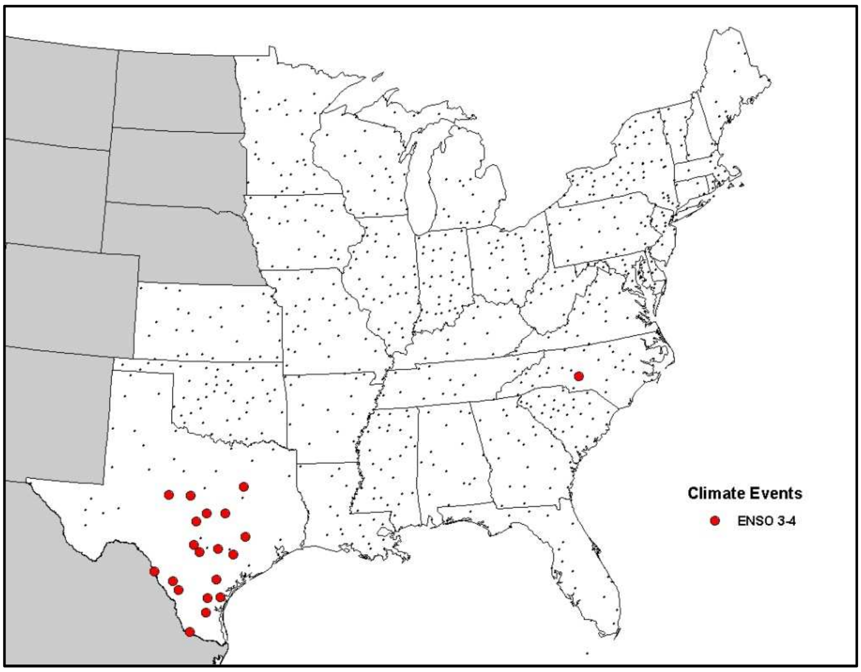


Figure 32: Correlation (95% of confidence level) between TC rainfall and Niño 3.4 annual average. Red circles represents negative correlation at α=0.05.

V CONCLUDING REMARKS

This chapter summarizes the major objectives and conclusions of this research project. Chapters II to IV each represents a paper being prepared for submission to international scientific journals for publication. The three primary objectives of this dissertation were:

1. Study the TC rainfall contribution to the total rainfall by month and season (June to November) from 1960 to 2007 and compare with previous studies.
2. Assess trends in total volume and area of TC rainfall in the Eastern United States and related to ENSO and AMO.
3. Asses the impacts of ENSO and AMO on the geographical variability of TC rainfall as well as to assess spatial variability in temporal trends.

After summarizing the data methods, I will provide a brief synopsis of each chapter and its conclusion.

DATA AND METHODS

The data and methods, for the most part, are relevant to each of the three analysis chapters**.** This research used data from the HURDAT dataset, including the track and the intensity of each storm from 1931-2007 (Jarniven, Neumann and Davis 1984), and rainfall data extracted from monthly rainfall observations from the United States Historical Climatology Network Monthly Precipitation and Temperature Data -USHCN (Williams et al., 2007). In addition, daily precipitation was updated for the same stations through the Southern Regional Climate Center (SRCC) Applied Climate Information System (ACIS). TC-related precipitation was considered any precipitation produced by hurricanes and tropical storms for all storms making landfall in the Eastern U.S., and for all storms that where within an offshore distance of 500 km.

Based on this storm characteristic, 717 weather stations were selected from 34 states.

The ENSO index used in this study was obtained from the Japan Meteorological Agency (JMA). The AMO dataset was obtained from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory/Physical Science Laboratory. Note that AMO phases were classified by year as positive or negative based on the six months (June-November) moving average. ENSO was classified by the year of occurrence and the phase (positive, neutral and negative). This study frames the definition of TC rainfall based on the general question: what distance from the center of a TC can observed rainfall be accurately associated with that storm? This dissertation used a radius of a 500 km (310 miles) centered on each storm track, based on the HURDAT dataset, to select the weather stations; the TC precipitation was assumed symmetric around the storm center.

Objective One

The first objective was to determine the contribution of TCs to June-November rainfall in the Eastern United States. The period of 1960-2007 has 287 hurricanes and 219 tropical storms, however, only 50 hurricanes and 104 tropical storms have made landfall, as defined by the National Hurricane Center, in the Eastern U.S. between June and November. In addition, 76 TCs were included in this study that tracked within the 500 km threshold to shore bringing the total number of storms included in this study to 220 with an average of 4.6 storms per year. The study period displays annual represents 62% of all hurricane and tropical storm landfalls in the United States.

Storm days (SDs) represents the number of days that have one or more tropical storms landfall or within 500-km from the U.S. coast. The five-year moving average shows a negative trend from the 1970s to the early 1990s and a positive trend after that. September has the highest seasonal SD percentage at 45%.

Storm track density represents the density of linear features in the neighborhood of each output raster cell. Each month during the Atlantic hurricane season (June to November) was compared between two periods, 1931-1960 and 1960-2007. Overall the storm track density showed an intraseasonal variability and a slight shift in the high density eastward from 1931-1960 to 1960-2007 period.

TC rainfall contribution over Eastern United States presents interannual and intraseasonal variability. Seasonally (June to November), Florida receives the maximum amount of TC rainfall with 14-16 cm, decreasing further inland. TC rainfall percentages change geographically from June to November. The same pattern was found by Cry (1967) and Knight & Davis (2007). November receives the least amount of TC rainfall, and September the highest. In September, North Carolina, Virginia, and South Alabama present more than 30% of TC rainfall contribution. After September, the number of storms begins to decrease and fewer storms produce inland rainfall.

Objective Two

The focus of the Chapter III was to analyze the possible relationship of TC rainfall with climate indices such as ENSO and AMO, and identify if there are any trends in the amount of TC rainfall between 1960 and 2007. Chapter III showed that averaging the number of stations by the number of storms per year presented great annual variability with a slight negative trend through time. The total rainfall accumulated by year during 1960-2007 showed a dry period (1960s-1970s) followed by interannual oscillations between dry and wet periods. Overall, the total rainfall in the eastern U.S. presents a significant positive trend, which is in agreement with Karl and Knight (1998) from 1910-1996. TC rainfall from 1960-2007, presented high interannual variability and that is related to the frequency of tropical storms, intensity, and duration of those storms (number of storm days). The time series of U.S. landfalls shows a significant (99% of significance) negative trend from the1960s until the middle of the 1980s and a positive trend (non-significant) from the middle of the 1980 until 2007. TC frequency can be related to ENSO phases where the warm phase (El Niño) has a negative correlation. However, the cold and negative phases did not show any statistical correlation with TC frequency of TC landfalls. On the other hand, AMO showed a strong correlation (95% significant level) with TC rainfall. The AMO phases (positive and negative) have a strong correlation with TC rainfall.

Objective Three

The primary objective of Chapter IV was to asses the impacts of the ENSO and AMO on TC-induced rainfall totals at the individual station level. The period of 1931-1960 showed a higher number of SDs compared to 1961-2007. The combination of positive AMO phase and few El Niño events during 1931-1960 allowed more storms to affect U.S. coast. During the AMO (-) phase (1960s to 1990s) most of the years have SDs below average, and after 1990s, with the return of the AMO (+), SDs become positive again. Accumulated SDs by day during 1931-1960 and 1961-2007 showed different patterns. The first period was characterized by having August with the maximum SD and September and October with a bimodal distribution. The second period showed August with a bimodal phase and September with the highest number of SD. There is a clear shift in the SDs between those periods, with more SDs from 1931-1960 during the beginning of the season (June) and in the middle of the season (September), whereby they account later in the season from 1961-2007.Major storms (Cat 3-5) recorded during the 1960-2007 period shows a geographical shift during the hurricane season. They affect Gulf Coast stations at the beginning of the season (June and July), expanding to the U.S. East

Coast in August and September, and returning to the Gulf in October and November. Overall, east Florida, Louisiana, Mississippi, and south Alabama receives the highest frequency of major storms (MS) during the study period (31 -38% of all storms). MS frequency decreases inland and toward the NE U.S. coast, with less than 7% of total storms. The spatial distribution of the MS anomalies shows two regions with high frequency of MS during the study period (two standard deviation or higher); South Louisiana and from Florida to coastal North Carolina.

The last part of Chapter IV was focused on the relationship of TC rainfall time series and teleconnections. TC rainfall was separated from the non-tropical rainfall, and founded that several stations in the Gulf of Mexico and in the NE United States showed a positive annual trend (95% confident level). The first region is similar to the extreme precipitation region as founded by Curtis (2008); however, he founded no significant trend over the NE United States.

TC rainfall was tested with AMO and ENSO phases. There results showed that AMO (+) has a strong positive correlation (95% confident level) with TC rainfall over the United States east coast and in south Texas. This result, in general, is similar to Curtis' (2008) findings. However, Florida did not show any TC rainfall correlation with AMO, as founded by Curtis (2008). That suggests that non-tropical rainfall has a strong AMO correlation in Florida, since Curtis (2008) assumed that most rainfall occurring from August to October is caused by TC.

Finally, associations were tested between TC rainfall and ENSO phases. Results showed that only Texas stations had strong correlations with ENSO phases. ENSO (+) -El Niño - contributes negatively to the Texas TC rainfall and ENSO (-) -La Niña - contributes positively. In conclusion, an increase in TC rainfall over the region from Louisiana to Florida is caused by the frequency of MS during the study region with no correlation with AMO or ENSO.

SIGNIFICANCE OF FINDINGS

Rainfall produced by tropical storms could extend for hundreds of kilometers from their centers causing property damage, flooding, and mudslides in some regions (Larson, Zhou and Higgins 2005). However, the same tropical-related rain can be beneficial to regions experiencing drought. Knowing the spatial and temporal distribution of rain over the Eastern U.S. and its correlations with major climate factors such as AMO and ENSO will help in agricultural planning and mitigation strategies in the most affected regions. This study shows that AMO has a strong correlation with the total TC rainfall. Future scenarios suggests a few more decades in the positive AMO phase, hence more hurricane seasons with above average number of storms (Goldenberg, 2001), assuming the AMO remain in a warm phase. However, interactions with ENSO and other factors such as Quasi-Biennial Oscillation and vertical wind shear also contribute as a predictor of hurricane activity (Molinari, 2002).

FUTURE WORK

TC rainfall regularly represent a substantial part of the annual rainfall in the Southern United States coastal zones, but shows a high level of interannual and interdecadal variability. Nevertheless, TCs contribute significantly to river systems, replenishes reservoirs, and boosts groundwater supplies **(**Middelmann, 2007). Understanding TC behavior is critical to minimizing loss through urban planning and mitigation such as engineering levees, dams, buildings, water resources, and agriculture.

Future work should attempt to analyze regional contributions of TC rainfall, to assess regional vulnerability. There are also socioeconomic implications on regional scales because of varying levels of exposure along to the U.S. coastline. Another relevant research focus could be the correlation of the TC central pressure and the amount of daily rainfall. Finally case studies comparing “dry” TC seasons with “wet” seasons and possible correlations with teleconnections (El Niño, La Niña, and AMO), and upper atmospheric level conditions (500 mb surface, ridges and troughs, and water vapor satellite images) could lend further insight into TC rainfall in the Eastern United States.

BIBLIOGRAPHY

Adger, N W, T P Hughes, T P Folke, S R Carpernter, and J Rockström. "Social-Ecological Resilience to Coastal Disasters." *Science* 309 (2005): 1036-1039.

Anderson, S. "http:// www.ucgis.com from UCGIS Summer Assembly 2001." July 20-23, 2001. http://www.cobblestoneconcepts.com/ucgis2summer/anderson/anderson.htm (accessed September 20, 2008).

Bell, G D, and M Chelliah. "Leading Tropical Modes Associated with Interannual and Multidecadal Fluctuations in North Atlantic Hurricane Activity." *Journal of Climate* 19 (2006): 590-612.

Blake, E S, E N Rappaport, and C W Landsea. "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2006 (and Other Frequently Requested Hurricane Facts)." *NHC.* April 15, 2007. http://www.nhc.noaa.gov/Deadliest_Costliest.shtml (accessed July 08, 2008).

Bove, M C, J B Elsner, C W Landsea, X Niu, and J J O'Brien. "Effect of El Niño on U.S. Landfalling Hurricanes, Revised." *Bulletin of American Meteorological Society* 79, no. 11 (1998): 2477-2482.

Cerveny, R S, and L E Newman. "Climatological Relationships between Tropical Cyclones and Rainfall." *Monthly Weather Review* 128 (2000): 3329-3336.

Chapman, L, and J E Thornes. "The use of Geographical Information System In Climatology and Meteorology." *Progress in Physical Geography* 27, no. 3 (2003): 313-330.

Cione, J J, and E C Uhlhorn. "Sea SurfaceTemperature Variability in Hurricanes: Implications with Respect to Intensity Changes." *Monthly Weather Review,* 2003: 1783-1796.

Conlan, R, and R Service. *El Niño and La Niña: Tracing the Dance of Ocean and Atmosphere.* http://www7.nationalacademies.org/opus/elnino_11.html (accessed 10 08, 2008).

Cry, George W. "Effects of Tropical Cyclone Rainfall on the Distribution of Precipitation over the Eastern and Southern United States." Vol. 1. Professional Paper Environmental Sciences Services, 1967. 66.

Curtis, S. "The Atlantic multidecadal oscillation and extreme daily precipitation over the US and Mexico durin the hurricane season." *Climate Dynamics* (Springer Berlin / Heidelberg) 30, no. 4 (03 2008).

Dong, B, R T Sutton, and A A Scaife. "Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures." *Geophysical Research Letters*, 2006: L08705.

Earls, J, and B Dixon. *http://www.cobblestoneconcepts.com/ucgis2summer/anderson/anderson.htm.* http://gis.esri.com/library/userconf/proc07/papers/papers/pap_1451.pdf (accessed August 24, 2008).

Elsener, J B, and A B Kara. *Hurricanes of the North Atlantic: Climate and society.* Oxford University Press, 1999.

Elsner, J, J Kossin, and T Jagger. "The Increasing intensity of the strongest tropical cyclones." *Nature* 455, no. 4 (2008): 92-95.

Emanuel, K. *Divine wind -the history and science of hurricanes.* New York: Oxford University Press,, 2005.

Emmanuel, K. "A Statistical Analysis of Tropical Cyclone Intensity." *MONTHLYW EATHERREVIEW* 128 (2000): 1139-1152.

—. *Divine wind -the history and science of hurricanes.* New York: Oxford University Press,, 2005.

Enfield, D B, A M Mestas-Nunez, and P J Trimble. "The Atlantic multidecadal oscillation to rainfall and river flows in the continenta." *Gephysical Research Letters* 28, no. 10 (2001): 2077-2080.

Englenhart, P J, and A V Douglas. "The role of eastern North Pacific tropical storms in the rainfall climatology of western Mexico." *International Journal of Climatology* 21, no. 11 (2001): 1357-1370.

Field, A. *Discovering Statistics using SPSS.* SAGE Publications, 2005.

Glenson, B E. "Characteristics of tropical cyclone rainfall in the United States." *27th Conference on Hurricanes and Tropical Meteorology, Session 16C, Tropical Cyclones and Climate V - Atlantic Basin.* 2006.

Goldenberg, S B, C W Landsea, A M Mestas_Nunez, and W M Gray. "The recent increase in Atlantic hurricane activity: Causes and implications." *Science* 293, no. 5529 (2001): 474-479.

Gray, W. M. "Atlantic seasonal hurricane frequency. Part I: El Nino and 30 mb quasi-biennial oscillation influences." *Monthly Weather Review* 112 (1984): 1649-1668.

—. "Hurricanes and Climate Change: Assessing the Linkages Following the 2006 Season." *George Marshall Institute.* October 11, 2006. http://www.marshall.org/article.php?id=465 (accessed April 10, 2007).

Hart, R E, and J L Evans. "A Climatology of the Extratropical Transitions of Atlantic Tropical Cyclones." *Journal of Climate* 14 (2001): 546-564.

Hasegawa, A, and S Emori. "Tropical Cyclones and Associated Precipitation over the Western North Pacific: T106 Atmospheric GCM Simulation for Present-day and Doubled CO2 Climates." *SOLA* 1 (2005): 145-148.

Haylock, M. "Linear Regression Analysis for STARDEX." 2004. http://www.cru.uea.ac.uk/projects/stardex/Linear_regression.pdf (accessed 01 18, 2009).

Henderson-Sellers, A, et al. "Tropical Cyclones and Global Climate Change:A Post-IPCC Assessment." *Bulletin of the American Meteorological Society* 79 (1998): 19-38.

Holland, G J, and P J Webster. "Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend?" *Philos. Trans. R. Soc. Ser. A* 365 (Nov 2007): 2695– 2716.

Jarniven, B R, C J Neumann, and M.A D. Davis. "A tropical cyclone data tape for the North Atlantic basin, 1886–1983: contents, limitations, and uses." NOAA Tech. Memo., NWS NHC 22, pp.21, 1984.

Karl, T R, and R W Knight. "Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States." *Bulletin of the American Meteorological Society* 79, no. 2 (1998): 213-241.

Karl, Thomas R, et al. "Trends and variations of Hurricane related precipitation." *AMS Forum: Living in the Coastal Zone.* 2005.

Keim, B D, and G E Faiers. "Heavy Rainfall Distributions by Season in Louisiana: Synoptic Interpretations and Quantile Estimates." *Water Resources Bulletin* 32, no. 01 (1996).

Keim, B D, and K D Robbins. "Occurrence dates of North Atlantic tropical storms and hurricanes: 2005 perspective." *Geophysical Research Letters* 33 (2006): L21706.

Keim, B D, R A Muller, and G W Stone. "Spatial and Temporal Variability of Coastal Storms in the North Atlantic Basin." *Marine Geology,* no. 210 (2004): 7-11.

Keim, B.D. "Precipitation Annual Maxima as a Measure of Change in Extreme Rainfall Magnitudes in the Southern United States over the Past Century." *Southern Geographer* 39 (1999): 235-245.

Kerr, R.A. "A north Atlantic Climate Pacemaker for the Centuries." *Science* 288, no. 5473 (June 2000): 1984 - 1985.

Kim, T, S Jain, U Lall, B Rajagopalan, Y Kushnir, and Y Moon. *Extreme Floods and Precipitation Related to Tropical Storms and Their Low Frequency Climate Precursors : A Case Study of the East Coast of the United States.* http://kfki.baw.de/conferences/ICHE/2000-Seoul/pdf/151/PAP_170.PDF (accessed 08 12, 2008).

Klotzbach, P J. "Trends in global tropical cyclone activity over the past twenty years (1986-2005)." *Geophysical Research Letters* 33 (2006): L10805.

Klotzbach, P, and W Gray. *EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND U.S. LANDFALL STRIKE PROBABILITY FOR 2008.* 2008. http://hurricane.atmos.colostate.edu/Forecasts/ (accessed 10 7, 2008).

Knight, D B, and R E Davis. "Climatology of Tropical Cyclone Rainfall in the Southeastern Unite States." *Physical Geography* 28, no. 2 (2007): 126-147.

Knight, J R, C K Folland, and A A Scaife. "Climate impacts of the Atlantic Multidecadal Oscillation." *Geophysical Research Letters* 33 (2006): L17706.

Landsea, C W, N Nicholls, W M Gray, and L A Avila. "Downward trends in the frequency of intense Atlantic hurrcianes during the past five deacades." *Geophysical Research Letters* 23, no. 13 (1996): 1697-1700.

Landsea, C. W. "Counting Atlantic Tropical Cyclones back to 1900." *EOS, Transaction, American Geophysical Union* 88, no. 18 (2007): 197-208.

Landsea, C.W. "A Climatology of Intense (Major) Atlantic Hurricanes." *monthly Weather Review* 121 (1993): 1703-1712.

Landsea, Christopher W, Roger A Pielke Jr, Alberto M Mestas-Nuñez, and John A Knaff. "Atlantic Basin Hurricanes: Indices of Climatic Change." *Climate Change*, 1999: 82-129.

Larson, J, Y Zhou, and R W Higgins. "Characteristics of Landfalling Tropical Cyclones in the United States and Mexico: Climatology and Interannual Variability." *Journal of Climate* 18 (2005): 1247-1262.

Levene, H. "Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling." Edited by I. Olkin et al., 278-292. Stanford University Press.

Lyon, Bradfield, and Suzana J Camargo. "The seasonally-varying influence of ENSO on rainfall and tropical cyclone activity in the Philippines." Feb 26, 2008. http://www.springerlink.com/content/d674p35176p48516 (accessed July 08, 2008).

Lyons, S. "U.S. Tropical Cyclone Landfall Variability:1950-2002." *Weather and Forecasting* 19 (April 2004): 473-480.

Mallin, M A, and C A Corbett. "How Hurricane Attributes Determine the Extent of Environmental Effects: Multiple Hurricanes and Different Coastal Systems." *Estuaries and Coasts* 29, no. 6A (2006): 1046–1061.

Manzello, D P, M Brandt, T B Smith, D Lirman, J C Hendee, and R S Nemeth. "Hurricanes benefit bleached corals." *PNAS*, 2007: doi:10.1073/pnas.0701194104.

Marks, F D. *Hurricanes:Encyclopedia of Atmospheric Sciences.* London, UK: Elsevier Science Ltd, 2003.

Martin, J D, and T W Simpson. "Use of Kriging Models to Approximate Deterministic Computer Models." *American Institute of Aeronautics and Astronautics* 43, no. 4 (April 2005).

Mather, J.R. "Climatology: Fundamentals and Applicarions." 412. McGraw-Hill, 1974.

Matyas, C. *Analyzing Tropical Cyclone Rain Shields According to Storm Size.* 2006. http://ams.confex.com/ams/pdfpapers/108831.pdf (accessed 08 12, 2008).

Matyas, C. "Quitifying the Shape of U.S. Landfalling Tropical Cyclones Rain Shields." *The Professional Geographer* 59, no. 2 (2007): 158-172.

Merril, R T. "A Comparison of Large and Small Tropical Cyclones." *Monthly Weather Review* 112, no. 7 (1984): 1408-1418.

Middelmann, M H. Chap. 4 in *Natural Hazards in Australia: Identifying Risk Analysis Requirements*, by M H Middelmann, edited by M H Middlemann, 42. Camberra, 2007.

Mo, K C. "The Association between Intraseasonal Oscillations and Tropical Storms in the Atlantic." *Monthly Weather Review* 128, no. 12 (2000): 4097-4107.

Molinari, R L, and A M Mestas-Nuñez. "North Atlantic Decadal Variability and the Formation of Tropical Storms and Hurricanes." *Geophysical Resaerch Letters* 30, no. 10 (2003): 1541.

NASA, Goddard Space Flight Center. "Smaller Strorms Drop Larger Overall Rainfall in Hurricane Season." *ScienceDaily*. December 11, 2007. http://www.sciencedaily.com/releases/2007/12/071210104022.htm (accessed July 1, 2008).

New, M, M Todd, M Hulme, and P Jones. "Precipitation Measurements and Trends in the Twentieth Century." *International Journal of Climatology* 21 (2001): 1899-1922.

Newmann, C J, B R Jarvinen, C J McAdie, and G R Hammer. "Tropical Cyclones of the North Atlantic Ocean, 1871-1999." *Historical Climatology Series 6-2,NOAA/NWS/NESDIS*, 1999: 206.

Nicholls, N, C W Landsea, and J Gill. "Recent trends in Australian region tropical cyclone activity." *Meteorology and Atmospheric Physics* 65 (1998): 197-2005.

Nyberg, J, B A Malmgren, A Winter, M R Jury, K H Kilbourne, and T M Quinn. "Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years." *Nature*. May 1, 2007. http://www.nature.com/nature/journal/v447/n7145/full/nature05895.html (accessed July 10, 2008).

Pfost, R L. "Operational tropical cyclone quantitative precipitation forecasting." *National Weather Digest,*, 2000: 61-66.

Phil, J E, and A V Douglas. "The role of eastern North Pacific tropical storms in the rainfall climatology of western Mexico." *International Journal of Climatology* 21, no. 11 (2001): 1357-1370.

Pielke Jr, R A, C Landsea, M Mayfield, J Laver, and R Pasch. "Hurricanes and Global Waming." *Bulletin of the American Meteorological Society*, November 2005: 1571-1575.

Pielke Jr., R A, and C W Landsea. "La Niña, El Niño, and Atlantic Hurricane Damages in the United States." *Bull. Amer. Meteor. Soc.* 80, no. 10 (1999): 2027-2033.

Pielke, R A, J Gratz, C W Landsea, D Colins, M A Sauders, and R Musulin. "Normalized Hurricane damage in the United States: 1900-2005." *Natural Hazards Review,* 2008: 29-42.

Rao, G V, and P D Macarthur. "The SSM/I estimated rainfall amounts of tropical cyclones and their potential in predicting the cyclone intensity changes." *Monthly Weather Review* 122, no. 7 (1994): 1568-1574.

Rappaport, E. *Inland Flooding.* http://www.nhc.noaa.gov/HAW2/english/inland_flood.shtml (accessed January 28, 2008).

—. "Inland Flooding." *National Hurricane Center.* 2008. http://www.nhc.noaa.gov/HAW2/english/inland_flood.shtml (accessed July 10, 2008).

Ren, F, B Gleason, and D Easterling. "Typhoon Impacts on China's Precipitation during 1957-1996." *Advances in Atmospheric Sciences* 19, no. 5 (2002): 943-952.

Ren, F, Y Wang, X Wang, and W Li. "Estimating Tropical Cyclone Precipitation from Station Observations." *Advances in Atmospheric Sciences* 24, no. 4 (2007): 700-711.

Rodgers, E B, R F Adler, and H F Pierce. "Contribution of Tropical Cyclones to the North Atlantic Climatological Rainfall as Observed from Satellites." *Journal of Applied Meteorology*, no. 40 (2001): 1785-1800.

Shapiro, L J, and S B Goldenberg. "Atlantic Sea Surface Temperatures and Tropical Cyclone Formation." *Journal of Climate* 11 (1998): 578-590.

Shult, J M, J Russel, and Z Espinel. "Epidemiology of Tropical Cyclones: The Dynamics of Disaster, Disease, and Development." *Epidemiol Rev* 27 (2005): 21-35.

Simpson, R H, and H Riehl. *The Hurricane and Its Impact.* Baton Rouge: Louisiana State University Press, 1981.

Srock, Alan F, L Bosart, and J E Molinari. "Precipitation distribution from landfalling tropical cyclones over the Southeast United States Coast." *Sixth Conference on Coastal Atmospheric and Oceanic Prediction and Processes.* 2005.

Tonkin, H, C W Landsea, G J Holland, and S Li. *Tropical cyclones and climate change: A preliminary assessment. Assessing Climate Change: Results from the Model*

Evaluation Consortium for Climate Assessment. Edited by W. Howe and A. Henderson-Sellers. Gordon and Breach, 1997.

Trenberth, K E. "The Definition of El Niño." *Bulletin of the American Meteorological Society* 78, no. 12 (1997): 2771-2777.

University of Florida. "New Tools Developed To Forecast Hurricane Rainfall Inland." *ScienceDaily.* June 20, 2007. http://www.sciencedaily.com¬/releases/2007/06/070619125642.htm (accessed July 10, 2008).

Vecchi, G A, and B J Soden. "Global Warming and the Weakening of the Tropical Circulation." *Journal of Climate* 20 (2007): 4316-4340.

Vitart, F, and J L Anderson. "Sensitive of Atlantic Tropical Storm Frequency to ENSO and Interdecadal Variability of SSTs in an Ensemble of AGCM Integrations." *Journal of Climate* 14 (2001): 533-545.

Watson, R T, M C Zinyowera, and R H Moss. *Intergovernmental Panel on Climate Change.* 1996. http://www.ipcc.ch/ipccreports/sres/regional/184.htm (accessed 09 17, 2008).

Webster, P G, G J Holland, J A Curry, and H -R Chang. "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environmen." *Science* 309 (5742) (2005): 1844-1846.

Wendland, W M. "Tropical Storm related to Sea SUrface Temperatures." *Journal of Applied Meteoroology* 16 (1977): 477-481.

Williams, C N, M J Menne, R S Vose, and D R Easterling. *United States Historical Climatology Network Monthly Temperature and Precipitation Data.* 2007. http://cdiac.ornl.gov/epubs/ndp/ushcn/usa_monthly.html (accessed 10 3, 2007).

VITA

Ricardo C. Nogueira was born in January 1962, in Pelotas, Rio Grande do Sul, Brazil. He graduated from Colegio Municipal Pelotense in 1981. He attended the Federal University of Pelotas and received his Bachelor of Science in Meteorology in February 1986. He worked as chief meteorologist for Fruit Growers of Fraiburgo Association, in Fraiburgo, Brazil, from 1986-1991. His second job was a meteorologist specialized in weather aviation; working for INFRAERO (The Brazilian Airport Infrastructure Company) Guarulhos-Sao Paulo, Brazil, from 1992-1997 . His last job was a weather anchor, in The Weather Channel. He entered Graduate School at Western Michigan University in the Department of Geography in August 2003. He received his Master of Science degree in geography in June 2005. While pursuing both his master’s and doctoral. degrees, he served as teaching assistant in both universities. He is father of Michele, Ingrid and Ricardo and his parents are Mr. and Mrs. Antonio Nogueira of Pelotas, Brazil.