Lightning Flash Rate in the Lake Maracaibo, Venezuela Related to Sea Surface Temperatures and Tropospheric Air Flow

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LIGHTNING FLASH RATE IN THE LAKE MARACAIBO BASIN, VENEZUELA RELATED TO SEA SURFACE TEMPERATURES AND TROPOSPHERIC AIR FLOW

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Geography and Anthropology

by

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List of Acronyms

AMM  Atlantic Meridional Mode
AMO  Atlantic Multidecadal Oscillation
AWP  Atlantic Warm Pool
CAPE Convective Available Potential Energy
CC   Cloud-to-Cloud
CG   Cloud-to-Ground
CL   Catatumbo Lightning
CLLJ Caribbean Low-Level Jet
DJF  December, January, February
ENSO El Niño Southern Oscillation
GHRC Global Hydrology Resource Center
IC   Intra-Cloud
IRIDL International Research Institute Data Library
ITCZ Inter-Tropical Convergence Zone
JJA  June, July, August
LEO  Low Earth Orbiting
LFR  Lightning Flash Rate
LIS  Lightning Imaging Sensor
LMB  Lake Maracaibo Basin
MAM  March, April, May
MB-NLLJ Maracaibo Basin Nocturnal Low-Level Jet
MJO  Madden-Julian Oscillation
NCAR National Center for Atmospheric Research
NCEP National Center for Environmental Prediction
NOAA National Oceanic and Atmospheric Administration
OTD  Optical Transient Detector
PBL  Planetary Boundary Layer
PDO  Pacific Decadal Oscillation
SAL  Saharan Air Layer
SON  September, October, November
SST  Sea Surface Temperature
TRMM  Tropical Rainfall Measuring Mission
TUTT  Tropical Upper Tropospheric Trough
UL  Upper Level
WHWP  Western Hemisphere Warm Pool
Abstract

Northern Venezuela’s Lower Maracaibo Basin (LMB) has the highest Lightning Flash Rate (LFR) density in the world. The area receives approximately 200 flashes/km² annually. Local topography as well as local and global scale climate drivers have been shown to influence the frequency of the lightning storms, known as “Catatumbo Lightning”. This research focuses on influences on LFR in the LMB by local and global sea surface temperatures and elements of local tropospheric air from 1996–2015. Sea surface temperature and tropospheric air data from the National Oceanic and Atmospheric Administration are used in Spearman rank correlations to determine relationships to LFR data (Global Hydrology Resource Center) in the basin. Oceanic regions were analyzed, including; the Caribbean Sea, the Pacific Ocean (El Niño Region) and the Atlantic Ocean (Atlantic Meridional Mode region). Four tropospheric elements were analyzed, including temperature, specific humidity, u-wind velocity, and v-wind velocity. All elements were analyzed at all mandatory pressure levels (1000 mb – 200 mb). The data sets are on a 2.5° x 2.5° gridded scale, with the exception of SST which is 1° x 1°.

Many statistically significant correlations were found between LFR and all variables included. Positive relationships were found between SST and LFR in the Caribbean Sea during the warmer seasons and negative relationships were found in the tropical Pacific on an annual scale. Many positive relationships were found between LFR and temperature, over the Caribbean and northern South America, mainly within the planetary boundary layer. There were also a large negative correlation extent between LFR and temperature over South America on the 200 mb level. Positive correlations were found between LFR and relative humidity over the Atlantic Ocean, east of Cuba during the warmer seasons and negative correlations were found during all seasons, mainly to the east of South America into the Atlantic Ocean. Positive relationships between LFR and u-wind were found over the Atlantic, Caribbean, and South America during all seasons at various pressure levels.
Between June and November, negative correlations were found in the upper atmosphere to the east of the Lake Maracaibo Basin (LMB) extending into the Atlantic. Positive correlations were found over the LMB between 850 mb and 500 mb between December to May. Many more correlations were found. Influencing factors may include the Western Hemisphere Warm Pool, the El Niño Southern Oscillation, the low-level jets and shifting circulation patterns.

Lightning is a dangerous atmospheric phenomenon and is responsible for hundreds of human deaths as well as for substantial economic loss annually. Further understanding of climate drivers responsible for the production of lightning will prove useful for the advancement of seasonal predictions, which can assist mitigation for protection of those living in lightning prone regions.
Chapter 1
Introduction

1.1 Background

Lightning is a dangerous atmospheric phenomenon that occurs regularly on every continent, with the exception of Antarctica. Lightning flashes are ten times hotter than the sun, they travel over 100 million kilometers per hour and strike the Earth approximately 100 times per second (NOAA, 2016). The frequency, strength, and unpredictable nature of lightning makes it second only to floods as the most dangerous natural hazard to humans. In the United States, 334 people have been killed directly and indirectly by lightning since 2006 (NOAA, 2016). The average death toll worldwide is 200 people per year. In addition to human casualties, a single lightning strike can damage infrastructure, blow out communication and power lines, kill livestock, and start house or forest fires. Annual insurance claims for lightning-related damage and injury exceed one billion dollars per year in the United States (NOAA, 2016).

Though the basics of lightning are known, it is still a mysterious phenomenon that is not entirely understood. During the formation of thunderstorms, clouds become polarized due to the collision of water droplets and ice crystals which separate protons from electrons, creating what is known as charge polarization within the cloud. Negative charges typically collect at the base of the cloud, transported by downdrafts, and positive charges travel to the top of the cloud, transported by updrafts. Lightning is created as an attempt to neutralize this polarization. The electrical field surrounding the storm strengthens and eventually ionizes and becomes plasma through which a current (lightning) can flow. This path is referred to as a step-leader and creates a path from the cloud to the ground, another cloud, or a different part of the same cloud. The negative charge at the base of the cloud repulses negative charges on the ground, other clouds, homes or other places nearby. These, now positively charged, objects respond by sending what are known as positive streamers.
If and when the step-leader and positive streamer connect; they create a path by which the electricity flows which neutralizes the polarization. This transport of electricity is the visual flash known as lightning.

Lightning has become significant in the study of climate variability due to its relationship to shifting temperature and precipitation patterns (Williams et al., 2005; Nath et al., 2009; Collier et al., 2012). Global circulation patterns such as the El Niño Southern Oscillation (ENSO) are of interest due to their relationship to LFR (Hamid et al., 2001; Chronis et al., 2008). Changes in LFR and distribution may be an indicator of a changing climate (Christian et al., 2003; Dwyer and Rassoul, 2009) in addition to climate variability is also of interest as c. The understanding of lightning within the realm of climate variability brings up a number of questions regarding the mechanisms required for lightning production. These include drivers that influence seasonal and daily variability of necessary lightning formation mechanisms. Changes in these patterns or mechanisms may be responsible for variation in LFR across the globe.

The continental tropics receive the majority of global lightning due to the relatively consistent convectional lifting from high surface temperatures, abundant moisture, and dynamic forcing mechanisms. This makes the region ideal for studying lightning patterns (Pinto et al., 2007; Collier et al., 2012). Within the tropics, northern Venezuela is home to one of the world’s most frequent set of lightning storms and receives the most lightning flashes in the world (Albrecht et al., 2009; Muñoz and Díaz-Lobatón, August 8-10, 2011; Albrecht et al., 2011; Muñoz et al., 2016; Bürgesser et al., 2012). These lightning storms are referred to as a single phenomenon and are known locally as “Relámpagos del Catatumbo” or “Catatumbo Lightning” (CL) (Muñoz and Díaz-Lobatón, August 8-10, 2011). These nocturnal storms occur in the Lake Maracaibo Basin (LMB) region of northwestern Venezuela and occur over 200 nights per year and last on average 10 hours per night. The storms occur over the same general region and have been recorded in unofficial documents for over 500 years (Muñoz and Díaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012;
Munoz et al., 2016). The high frequency and relatively consistent spatial range of these storms allows for a broad examination of potential environmental influences on LFR in the tropics.

1.2 Research Questions

This research focuses on variations in LFR related to potential links to sea surface temperature (SST) and elements of tropospheric parameters, including moisture, temperature, and wind flow. The research is intended to illustrate potential climate drivers that influence LFR and act as a foundation for future finer scale analysis. In this thesis, the research questions include:

1) What are the statistical relationships between LFR and SST in portions of the Caribbean Sea, Atlantic Ocean, and Pacific Ocean on annual and seasonal time scales? It is expected that an increase in SST in the Caribbean Sea and Atlantic Ocean will result in an increase in LFR in the LMB during all seasons due to the relationship between moisture and temperature to LFR. It is expected that an increase in SST in the eastern Pacific Ocean will decrease LFR due to shifting circulation patterns from changes in pressure gradients.

2) What are the statistical relationships between LFR and tropospheric air temperature at various pressure levels? It is expected that there will be a positive correlation between temperature and LFR over the LMB and Caribbean due to relationships between temperature and thunderstorm development.

3) What are the statistical relationships between LFR and tropospheric specific humidity? It is expected that there will be a positive correlation between specific humidity and LFR from the surface to the middle troposphere during spring and summer over the LMB and the western tropical Atlantic Ocean due moisture advection.

4) What are the statistical relationships between LFR and zonal and meridional tropospheric winds? It is expected that zonal winds within the planetary boundary layer (PBL) will be negatively correlated to LFR due to the influence of the zonal low-level jet. Merid-
ional winds are expected to show positive relationships in the lower levels of the atmosphere due to the influence of the nocturnal low-level jet.

1.3 Study Area

The study region for LFR is confined to a small area over the LMB in northwestern Venezuela and is bounded by 8.5°N–11.5°N and 70.5°W–72.5°W (Figure 1.1). These coordinates were chosen based on the work of Muñoz and Diaz-Loabatón (2011), who confirmed that this small region receives the vast majority of flashes in the region. The coordinates were originally chosen based on fine resolution lightning flash rate density as illustrated by LIS/OTD flash-rate data from the Global Hydrology Resource Center (GHRC) (Muñoz and Diaz-Lobatón, August 8-10, 2011).

The LMB is a structural basin that is surrounded on two sides (east and west) by arms of the Andes Mountains. To the east is the Perijá Range (peak: 3630 meters) extending along the Venezuela-Colombia border and to the west are the Méridas Andes (peak: 4,978 meters) extending past Lake Maracaibo in a northeast direction until nearly the edge of the Caribbean Sea. To the north of the basin are the Caribbean Sea and the Gulf of Venezuela, which feeds into Lake Maracaibo. This brackish lake is also fed by the Catatumbo River and is the largest lake in South America (Bürgesser et al., 2012). The LMB is generally considered a tropical humid climate environment, according to the Köppen Climate Classification (Peel et al., 2007); however, there are small pockets of warm, semi-arid and warm desert nearing the northern boundary of Venezuela. The seasons of the LMB, like most tropical regions, follow precipitation patterns and are denoted "dry" and "wet" seasons. The driest months of the LMB are December, January, and February and the wetter months are September, October, and November. The complex topography of the LMB is an important contributing factor to the production of the recurring CL storms.

The study area is also expanded to encompasses large portions of the Pacific and Atlantic Oceans and the entire Caribbean Sea as well as a larger region of the surrounding atmosphere. The oceanic domain used in this study is bounded by 25°S x 25°N and 165°E
Figure 1.1: Lake Maracaibo Basin, Venezuela 7.5°N–11.5°N — 70°W–73°W.
to 15°E. The SST data were chosen to encompass the Western Hemisphere Warm Pool (WHWP) region of the Caribbean Sea, the Atlantic Meridional Mode (AMM) region of the Atlantic Ocean and the entire Niño region of the Pacific Ocean. The atmospheric domain is bounded by 6°S x 26°N and 94°W to 46°W. This domain was chosen to encompass wind flow patterns and temperature and precipitation regimes of northern South America (see Figure 1.2).

Figure 1.2: Oceanic and Atmospheric Domains

When analyzing climate variability, it is important to consider the geographic scale at which variables are examined, as there are a wide range of potential interactions among differing scales. According to Wilbanks and Kates (1999), most climate variability research is focused on “top-down” scaling, that is, from a larger scale to a smaller scale. Climate works differently at different scales and it is important to acknowledge the difficulty of attempting to include all possible factors at play. In this research, LFR in a small geographic region is analyzed in relation to larger-scale climate and ocean systems, utilizing the “top-down” method. Another factor to consider when examining scale, is the application of findings to other geographic regions. For example, the study of large-scale influence on one localized domain, such as in this study, may not translate the same to another, even similar, geographic region. With that said, this study is mainly intended to analyze larger-scale climate variables on LFR in the LMB while taking into account local influence. Though results may not perfectly translate to other geographic regions, it is also intended to act as
a generalized analysis of potential drivers on LFR in other tropical regions. However, to make conclusive remarks about different geographic regions, local influences will need to be included in separate studies.

1.4 Significance of Research

1.4.1 Intellectual Merit

Characterizing lightning in various regions of the world is important for advancing prediction applications as well as furthering thunderstorm and lightning research efforts (Muñoz et al., 2016). Much of the tropics is uninhabited or has a sparse population, making land data observation difficult. Use of satellite lightning data enables research in remote areas. The study of lightning in the most lightning-prone region in the world will advance the understanding of the affects of global and local climate drivers on lightning production in the tropics.

1.4.2 Broader Impacts

Advancement in knowledge of the workings of the climate and weather in the tropics are important for the livelihood of those who reside in lightning-prone areas due to the number of deaths and injuries from lightning (NOAA, 2016). Many economies can be adversely impacted by weather and climate change (Mussetta and Barrientos, 2015; Narayanan and Sahu, 2016). Venezuela’s economy is heavily reliant on the export of oil, and lightning can cause damage to the extraction systems as well as set fire to oil storage tanks. Prediction of storms may allow for advanced protection of the tanks and oil economy. Any advancement in the knowledge of how and why these storms occur may help improve earlier prediction. Early prediction used as a tool for safety mitigation in the LMB can be applied to many lightning-prone regions of the world.
Chapter 2
Literature Review

2.1 Lightning in the Tropical Environment

2.1.1 Tropical Climatology

Lightning is produced in thunderstorms formed by convective, horizontal convergence, or frontal uplift. To produce lightning, thunderstorms must have uplift (Williams et al., 2005; Chronis et al., 2008; Nath et al., 2009), moisture (Sátori et al., 2009), updraft and downdraft (Williams et al., 2005), and a cloud top tall enough to form ice crystals (Williams et al., 2005). The vast majority of lightning worldwide occurs within the continental tropical regions (Christian et al., 2003; Williams et al., 2005; Pinto et al., 2007; Nath et al., 2009; Price, 2009). The boundaries of the tropics are defined in a number of ways, but this thesis defines the tropics by latitudinal boundaries. Areas that fall between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S) are considered tropical as the majority of the region shares a similar general climate. The similarity in climate in the tropics is due to the solar declination, which is at a direct (or near-direct) angle throughout the year. The sunlight angle in the tropics creates consistently high temperatures, a heightened troposphere, and abundant water vapor content which is the primary reason for the high frequency of lightning activity (Sátori et al., 2009).

The reason for the high LFR in the tropics is due, in part, to the high frequency of storms rather than the intensity of storm systems, as it is in the middle latitudes. The formation of tropical thunderstorms are different than those formed in higher latitudes in a number of ways. Temperature gradients in the tropics are minimal due to minimal annual variation in solar radiation, whereas many thunderstorms at higher latitudes are formed by frontal systems created by large temperature gradients. Tropical temperatures do not fluctuate greatly and are influenced by atmospheric elements such as prevailing winds,
SST, cloud cover, and precipitation. In addition to frequently warm tropical air, tropical precipitation often exceeds evaporation resulting in frequently moist continental air near the surface. In general, the lack of large temperature (and therefore pressure) gradients, make tropical air relatively homogeneous and any weather disturbances are caused by thermal convection, pressure shifts, moisture, and wind velocity. Microscale and mesoscale systems are known to be more influential on tropical climate than are synoptic systems (COMET, 2011). However, certain synoptic and global scale systems and patterns influence weather in the tropical environment and are discussed in detail in Section 3.2.

The LMB is located in the deep convective region of the tropics. This region is influenced by global circulation patterns, tropical climate drivers, and local climate drivers. The following sections describe the climatological and meteorological influences on weather in the LMB, both locally and globally.

2.1.2 Catatumbo Region

Three regions known as “chimneys” are most prone to lightning production: central Africa, South America, and Southeast Asia (Christian et al., 2003; Williams et al., 2005; Price, 2009). Within these regions are localized spots that receive relatively frequent and consistent lightning. Among these is northwestern Venezuela, which is home to unique persistent thunderstorms that occur at nearly the same time of night throughout much of the year.

Catatumbo Lightning (CL) is a meteorological phenomenon consisting of a collection of nocturnal thunderstorms which occur on average 200 nights per year and last up to ten hours per night (Muñoz and Diaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012; Muñoz et al., 2016). The majority of lightning occurs between the hours of 7:00pm and 4:00am local time (11:30pm–8:30am UTC). The storms always occur in the same general location over Lake Maracaibo in northwestern Venezuela, and are thus referred to as a single phenomenon and considered the most persistent thunderstorm in the world (Muñoz et al., 2016). The region recently became recognized as the area with the densest LFR in
the world (Albrecht et al., 2009; Muñoz and Diaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012; Muñoz et al., 2016). The flashes are mainly Intra-Cloud (IC) and Cloud-to-Cloud (CC), but Cloud-to-Ground (CG) flashes are not uncommon (Bürgesser et al., 2012).

Reports of the average annual number of lightning days in the LMB varies from study to study, which is likely due to the progressive improvement of data collection methods (Bürgesser et al., 2012). Before use of satellites, LFR data were recorded using keraunic instruments which calculate lightning based on audible thunder. As previously mentioned, much of the lightning in this region is CC or IC, which would not produce detectable thunder near the surface-based recording devices. Use of satellite sensors has vastly improved the accuracy of LFR data.

Although evidence that lightning has occurred in the same general location exists for the region’s entire documented history, recent research maintains that epicenters are confined to two central spots: (9.5°N; 71.5°W) in the southwest quadrant of Lake Maracaibo, and (9°N; 73°W) near the border of Venezuela and Colombia (Muñoz and Diaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012; Muñoz et al., 2016).

The region is surrounded on three sides (east, south, and west) by the Andes Mountains, with warm waters of the Caribbean Sea to the north and a swampland basin south of Lake Maracaibo. Researchers agree that the CL storms occur due to the complex topography which allows for consistent vertical development of convective clouds (Muñoz and Diaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012). In addition to normal tropical convection, the consistent vertical development is also due, in part, to the clashing of two differing air masses that move continuously across the LMB. Cold, drier air from the Andes Mountains meets warm, moist air blowing from the Caribbean Sea, creating a thermal gradient ripe for producing convective storms, this makes the climatology of the LMB unique as tropical environments typically do not have large thermal gradients. The two air masses meet over the LMB and are restricted by the surrounding mountains and this facilitates
additional boundary uplift. Interannual atmospheric circulation features also affect the region (Muñoz and Diaz-Lobatón, August 8-10, 2011; Muñoz et al., 2016).

To date, lightning-based research in the LMB has focused on surface-level climate drivers. While clearly important, surface weather can also be influenced by SST and tropospheric winds on larger spatial and temporal scales (McGregor and Nieuwolt, 1998).

Influence of Tropospheric Air

The troposphere is the region of the atmosphere where weather, as we know it, occurs and where the majority of general circulation takes place (McGregor and Nieuwolt, 1998). Surface-level winds are influenced by several forcing mechanisms, such as frictional drag, re-radiation of heat, and shifting due to restrictions of orographic boundaries. In the tropics, surface winds are dominated by easterly trade winds that move toward the equator from east to west in each hemisphere (from the northeast in the northern hemisphere and southeast in the southern hemisphere). This airflow converges near the equator, creating a rising flow that moves toward the subtropics. This flow of air creates a counterflow aloft, creating prevailing westerly winds (west to east) at the 200 mb level (Hidore et al., 2009).

Winds in the middle troposphere can enhance or diminish thunderstorms through wind shear. Storms are also steered in the middle troposphere. The middle troposphere can also influence characteristics of the surface and upper level (UL) winds. Variations in UL winds lead to changes in surface conditions, and changes in surface flow influence LFR density (COMET, 2011). More specifically, variations in temperature and pressure gradients lead to surface convergence and divergence and enhanced or suppressed wind shear. When two air streams meet in the troposphere they will either converge or diverge. Convergence of air masses aloft will cause sinking and a divergence at the surface. Conversely, when air diverges aloft, there will be a convergence at the surface (McGregor and Nieuwolt, 1998). Converging air at the surface will cause lower pressure and result in convection, which will increase the chance of lightning production. Divergence at the surface elicits higher pressure
(low pressure aloft) which results in less upward convection, and a potential decrease in lightning.

UL winds are mainly affected by the pressure gradient force (McGregor and Nieuwolt, 1998). UL tropospheric air can influence suppression or enhancement of thunderstorms through vertical wind shear and entrainment. Vertical wind shear is the change in wind speed or direction with height and is an important mechanism for the development of convective storms, as it can enhance or diminish the strength of the draft. Wind shear can enhance a thunderstorm by removing ascending air from the updraft, allowing for continued growth. It can also diminish a thunderstorm by removing ascending air too quickly, or by flowing in the opposite direction of the air within the storm structure. In a tropical thunderstorm, entrainment is the pulling in of drier air, thereby diminishing the growth. Shear and dry air intrusions are important elements of weather to consider when studying LFR.

Influence of Sea Surface Temperature

SSTs have a substantial influence on weather and climate across the globe and play a major role in developing climate regimes. Oceans absorb and distribute heat, and provide moisture. Changes in SSTs can change pressure gradients, which can alter weather and produce or suppress thunderstorms. In general, an increase in SST should enhance thunderstorms and increase LFR. Evaporation of moisture from nearby bodies of water contributes to the formation of thunderstorms. Evaporation usually increases with increasing temperature and, as SSTs increase, the evaporation rate also usually increases (COMET, 2011). Considering moisture is crucial to the development of strong thunderstorms, an increase in evaporation due to higher SSTs should increase LFR (COMET, 2011). SST is closely tied to the atmosphere and is altered by many coupled ocean-atmosphere dynamics on varying spatial and temporal time scales. These are discussed in more detail in the next section.
2.1.3 Climate Variability Related to LFR

Fluctuation and variability of SSTs and tropospheric winds can alter “normal” weather around the world. Variations occur on various temporal scales. These fluctuations and variations are important to acknowledge, as they can greatly affect LFR. Microscale and mesoscale systems are the major influences on the formation of everyday tropical thunderstorms. However, synoptic-scale climate variations also play a role in the distribution, fluctuation, and frequency of weather and climate in the tropics. The tropics are influenced by a number of specific fluctuations in climate on various temporal and spatial scales. Northwestern Venezuela is known to be influenced by shifts in global atmospheric, oceanic and coupled ocean-atmosphere patterns such as the Walker Circulation, El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Madden-Julian Oscillation (MJO), Atlantic Multidecadal Oscillation (AMO), Atlantic Warm Pool (AWP), Atlantic Meridional Mode (AMM) and Western Hemisphere Warm Pool (WHWP). Northern Venezuela is also influenced by dynamic local lifting mechanisms associated with the converging of trade winds at the Inter-Tropical Convergence Zone (ITCZ) (Collier et al., 2012), Caribbean Low-Level Jet (CLLJ) (Satori et al., 2009), Maracaibo Basin Nocturnal Low-Level Jet (MBNLLJ) (Muñoz et al., 2016), Tropical Upper Tropospheric Trough (TUTT), and dry-air intrusion of the Saharan Air Layer (SAL). These global and local influences are discussed in the following subsections.

Global Patterns Influencing LFR

The Pacific Walker Circulation is a zonal wind circulation in the tropical Pacific that is influenced by the flow of the trade winds. Easterly wind flow pushes warm surface water to the western side of the tropical Pacific Ocean, creating a region of low pressure and uplift. The rising air flows over the Pacific Ocean toward the west coast of South America where it descends over the low pressure region over the colder ocean water (Zhu and Stan, 2014).

Interannual coupled oceanic-atmospheric patterns such as the Walker Circulation are dominated by ENSO. ENSO is an interaction between the atmosphere and ocean in the
tropical Pacific. El Niño (warm phase), La Niña (cold phase), and neutral phases are the oceanic components of ENSO and are associated with changes in SST. The Southern Oscillation (SO) is the atmospheric component and is characterized by an east-to-west gradient of surface pressure anomalies across the equatorial Pacific. The Pacific Walker circulation is tied together with similar Walker-like circulations in the Atlantic which is also connected to ENSO (Giannini et al., 2000; Zhu and Stan, 2014). ENSO cycles every 2-7 years and affects weather over the entire world.

During an El Niño phase, the Walker Circulation triggers westerly anomalies over the tropical Pacific (Zhu and Stan, 2014) which allows water to push back to the west coast of South America, preventing cold water upwelling. This alters normal weather, including an increase in vertical wind shear over the western tropical Atlantic (Zhu and Stan, 2014). The increase of vertical wind shear can potentially decrease storm formation or intensity, which would presumably decrease LFR.

A La Niña phase occurs when the normal trade winds are strengthened and enhance the pooling of warm water in the western equatorial Pacific Ocean. This phase intensifies the normal pattern of the Walker Circulation, creating intensified rising in the western equatorial Pacific and intensified sinking near the east coast of South America. Normal weather features in these areas are intensified, with drier than normal conditions in South America and wetter than normal conditions over the western Pacific. The neutral phase of ENSO is associated with a “normal” Walker Circulation.

Hamid et al. (2001) found that surface air temperatures increase over land in most tropical regions during ENSO warm periods and decrease during cold periods. An increase in temperature over land elicits an expectation of increased lightning during warm phases (Hamid et al., 2001). Theoretically, an increase in air temperature will increase Convective Available Potential Energy (CAPE) (Hamid et al., 2001) which would increase the speed of updrafts. Since updraft speed is directly correlated to the frequency of lightning (Hamid et al., 2001; Williams et al., 2005; Chronis et al., 2008), it is expected that LFR would also
increase. Warming of SST in the western Atlantic and Caribbean also occurs during an El Niño event (Giannini et al., 2000). An increase in SST in the Caribbean creates conditions for an increase in convection and therefore presumably an increase in likelihood of lightning over the LMB.

The PDO is an oscillation of oceanic and atmospheric anomalies that occur in the north Pacific over a 20-to-30 year period. The oscillation is strongly correlated with ENSO and both are strongest in boreal winter. One study shows a link between the decadal variations in the PDO to fluctuations in the temperature at the tropical tropopause (the top of the troposphere), which are known to influence weather at the surface (Wang et al., 2016). The LFR, SST, and tropospheric air data sets in this study are too short to span a cycle of the PDO; however, it is important to take into account the effects it could possibly have on LFR.

The MJO is a 30-60 day atmospheric oscillation and is characterized by a large area of cloud and rainfall that propagates eastward around the equator at 4 to 8 ms$^{-1}$. Intraseasonal variability of rainfall within the tropics is dominated by the MJO. The active and inactive phases of the MJO are connected by reversing zonal circulation patterns. The oscillation tends to be inhibited during strong El Niño and La Niña events (COMET, 2011). The MJO is known to explain short-term weather patterns near the equator and has been shown to have impacts on the tropical atmosphere, including variations in tropical rainfall, UL winds, as well as surface pressure (McGregor and Nieuwolt, 1998).

The AMO is a SST fluctuation in the North Atlantic that has effects across the globe. There are two phases, cold and warm, and each phase can last between 20 and 40 years (Wang and Enfield, 2001, 2002). The AMO has been known to affect rainfall in northern Brazil and is associated with the movement of the ITCZ. The LFR data this study do not provide enough years to span a cycle of the AMO. However, it is important to take into account the effects it could possibly have on LFR. The AMO also dominates the Atlantic Warm Pool (AWP), which is a large pool of warm water that encompasses the Gulf of
Mexico, the Caribbean Sea, and the western tropical North Atlantic. The warm pool varies seasonally in location and extent (Wang and Enfield, 2001, 2002).

The AMM is the dominant coupled ocean-atmosphere variability in the Atlantic Ocean, and varies from interannual to decadal timescales (Smirnov and Vimont, 2011). The development of an AMM phase can be generated by ENSO (Patricola et al., 2014). The AMM is characterized by a fluctuation in the meridional gradient between SST in the North and South Atlantic (Patricola et al., 2014). During a positive (negative) phase, SSTs are warmer (cooler) than normal in the tropical North Atlantic and cooler (warmer) than normal in the tropical South Atlantic. During the positive phase of the AMM, a rise in SST in the North Atlantic causes the ITCZ to move northward, which is known to cause drought in northern South America (Smirnov and Vimont, 2011). Vertical wind shear decreases during the positive phase and this strengthens thunderstorms (Smirnov and Vimont, 2011; Patricola et al., 2014). Munoz et al. (2016) described the AMM as an important climate driver for LFR.

The WHWP is a section of the Caribbean Sea where temperatures exceed 28.5°C (Wang and Enfield, 2002). The warm pool is found to the west of southern Central America between March and November and expands to the east into the Gulf of Mexico and the Caribbean Sea between July and November. The WHWP extends over all of the Caribbean in September and October, which coincides with the LFR maxima in the LMB, while the temperature of the warm pool during the dry season is at its minimum (Muñoz and Diaz-Lobatón, August 8-10, 2011). The expansion and contraction of the WHWP creates enhanced or diminished convection in nearby landmass regions (Wang and Enfield, 2001). An increase in convection in the LMB would lead to enhanced thunderstorms and therefore increased LFR.

Local Influences

The ITCZ is a zone of low pressure near the equator that forms a narrow band of convective clouds and frequent precipitation around the globe and heavily influences storm
formation in the LMB. The ITCZ is caused by the converging of the easterly trade winds in the southern and northern hemispheres (Hidore et al., 2009). The ITCZ follows maximum solar radiation, so its position varies seasonally, but typically lags by one to two months. It moves north boreal summer and southward boreal winter. The migration of the ITCZ determines the wet and dry seasons for regions in the tropics (COMET, 2011). Local influences of the ITCZ in the LMB include the creation of a dry season during winter and a wet season during summer. Muñoz et al. (2016) show a considerable reduction in lightning during the dry months over the LMB. An uncharacteristic change in the migration of the ITCZ can influence the production of thunderstorms that produce lightning in this region.

The CLLJ is a maximum zonal wind that blows in the lower levels of the atmosphere near the Caribbean Sea, typically at the 925 mb level, but sometimes as high as the 700 mb level (Wang, 2007). It is known to suppress precipitation in northern Venezuela (Muñoz et al., 2016). The CLLJ has an annual cycle with two wind maxima; one in January–February and the other in July (Wang, 2007). The CLLJ has a minima in May and October, which overlaps with the most active period of CL storms (Muñoz and Díaz-Lobatón, August 8-10, 2011; Bürgesser et al., 2012; Muñoz et al., 2016). The NLLJ in the LMB is a nocturnal onshore breeze that blows into the region from the Caribbean Sea. The MBNLLJ is associated with bringing moisture into the LMB and influencing the production of the thunderstorms (Muñoz et al., 2016).

TUTTs are semi-permanent, quasai-stationary atmospheric troughs found in tropical oceans between 100 mb to 400 mb during summer. A portion of the TUTT is located over the Caribbean Sea as well as over northern South America (Fitzpatrick et al., 1995). Though TUTTs are typically associated with enhanced convection, in northern Venezuela the TUTT suppresses the development of thunderstorms due to the wind shear located at the southern flank of the trough (Elsner and Kara, 1999).

The SAL is a very warm, dry layer of air that originates in northern Africa. This layer of air moves westward over the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico
to South America while retaining its warm, dry properties (Dunion and Velden, 2004).

The SAL occurs during boreal spring, summer and early fall. The layer typically extends in the troposphere from 850 mb to 500 mb levels (Dunion and Velden, 2004; Wong and Dessler, 2005). In one study, the SAL was found below the 700 mb level with the largest temperature anomalies located around 850 mb, and the intrusion of this dry air layer was found to suppress thunderstorm production (Wong and Dessler, 2005). Thunderstorm suppression in the LMB would likely lead to a decrease in LFR.

Each of these global and local influences are considered when interpreting the results in Chapter 4.
Chapter 3
Data and Software

3.1 Data

3.1.1 Lightning Flash Rate

Lightning data used in this study come from two data sets that were merged in 1998. The first data set is from the Optical Transient Detector (OTD), which was an optical sensing instrument that was aboard the MicroLab-1 satellite from April 1995–March 2000. The instrument was at a 70° inclination, which allowed it to observe the majority of the Earth approximately 400 times per year, 2 minutes at a time (Boccippio et al., 2002; Christian et al., 2003). This sensor was able to detect flashes during the day and night. It measured IC, CC, and CG lightning flashes.

The second data set is from the Lightning Imaging Sensor (LIS), which is a lightning-sensing Low Earth Orbiting (LEO) instrument that was aboard the Tropical Rainfall Measuring Mission (TRMM) from November 1997–April 2015. The TRMM had an orbit at a 350 km altitude and detected total lightning including IC, CC, and CG flashes between 35°S and 35°N, which makes these data the most robust and reliable for the tropics and subtropics (Cecil et al., 2012). The sensor is optimized to locate and detect lightning with storm-scale resolution of 3-6 km over a large region (550 km) of Earth’s surface. The field of view is capable of observing a point for 80 seconds, which allows it to estimate the LFR of storms. The instrument records the time of occurrence of a lightning event, measures the radiant energy, and estimates the location (Christian et al., 2003). Missing data are denoted ”NA” and are not included in the calculation of the monthly mean. A drawback to LEO satellites is that they only capture data from each spot on Earth for a few minutes at a time and LFR is estimated. There are no ground-level lightning sensors in the LMB at this time.
Data were merged beginning January 1998 and are collectively known as LIS/OTD. These data sets are on a 2.5° x 2.5° grid and are relatively comprehensive for the tropics (Boccippio et al., 2002). However, a shortcoming of the data is the limited number of complete observing years (1998–2014). These limitations have hindered the study of LFR and make it difficult to determine statistically robust trends. Despite the limitations, Munoz et al. (2015) utilized these data in a study which determined CAPE and SST as significant predictors of LFR in the LMB on a lagged seasonal scale. Figure 3.1 is a lightning climatology provided by the Global Hydrology Resource Center (GHRC) using LIS data from 1998-2014. “Hotspots” are found in central Africa and Northern Venezuela.

Figure 3.1: Worldwide Lightning Climatology, GHRC, 1998-2014

3.1.2 Sea Surface Temperature

SST data used are the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) Sea Surface Temperature V2 (NOAA OI.v2 SST) weekly interpolated values from the Office of Oceanic and Atmospheric Research and Earth System Research Laboratory in the Physical Sciences Division (NOAA/OAR/ESRL PSD). Data are obtained by readings from ships and buoys on a 1°x1° grid and produced into a data set on a weekly basis beginning in January 1993 (Reynolds et al., 2002). NOAA OI.v2 SST monthly data sets are created by interpolating weekly data to daily data then averaging the daily values over a month (Reynolds et al., 2002). The coordinate variables are the centers
of the grid cells. In the case of missing values, interpolation of data is used to create mean values. Technical data values are minimal in this data set and are corrected quickly.

### 3.1.3 Tropospheric Air

Tropospheric air data were taken from NOAA’s National Centers for Environmental Prediction National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I. Four variables are considered: temperature, specific humidity, u-wind (zonal wind) and v-wind (meridional wind). The sign convention for a u-wind is that positive zonal values indicate that wind is flowing from west to east (westerly) and negative zonal values indicate that wind is flowing from east to west (easterly). The sign convention for a v-wind is that positive meridional values indicate wind is flowing from south to north (southerly wind) and negative meridional values indicate wind is flowing from south to north (northerly wind). Each variable is measured at 10 pre-defined barometric pressure levels (Table 3.1). Data are measured at pressure levels rather than heights to ensure calculations are consistent across the globe. Units of pressure are measured in millibars (mb). For reference, the average sea level surface pressure is 1013.25 mb. Temperature and specific humidity data are taken using radiosondes. U-wind and v-wind data were taken using rawinsondes. The data are on a 2.5°x2.5° grid and are recorded four times daily, then averaged into a monthly mean (Kalnay et al., 1996). The data extracted are the same spatial resolution as LFR and SST (January 1998 – December 2014). In the case of missing values, interpolation of data is used to create mean values. Technical data errors are minimal in this data set and are corrected quickly.

All mandatory levels of the troposphere, as denoted by the American Meteorological Society (AMS), are included in this study as each has a unique environment and therefore a potentially different effect on weather and the production of thunderstorms. Table 3.1 provides a description of each level as a justification for use in this study. Specific humidity data are only available between 1000 mb and 300 mb.
Table 3.1: Tropospheric Pressure Levels Used in this Analysis

<table>
<thead>
<tr>
<th>Pressure Level</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 mb (surface)</td>
<td>Surface weather</td>
</tr>
<tr>
<td>925 mb (457 meters)</td>
<td>Within PBL.</td>
</tr>
<tr>
<td>850 mb (1,500 meters)</td>
<td>Typically above the friction layer, where the surface does not influence wind speed, direction or temperature. Clouds and precipitation occur. Influence of the SAL. Peak of the Perijá Range, which bounds the LMB to the east.</td>
</tr>
<tr>
<td>700 mb (3,050 meters)</td>
<td>Usually considered the last level of the lower atmosphere. Troughs and ridges become well-defined. Temperature advection also occurs at this level. Influence of the SAL. Still below the peak of the Méridas Andes, which bound the LMB to the west.</td>
</tr>
<tr>
<td>500 mb (5,575 meters)</td>
<td>Referred to as the middle atmosphere. Free of influence of the arms of the Andes mountains. This is the level where many storms begin to be steered. Influence of the SAL.</td>
</tr>
<tr>
<td>400 mb (7,200 meters)</td>
<td>Approximate level where winds steer developed hurricanes. This is the first mandatory level in the upper troposphere. Influence of the TUTT.</td>
</tr>
<tr>
<td>300-200 mb (9,200-12,000 meters)</td>
<td>Upper levels associated with jet streams, as well as with convergence and divergence. Influence of the TUTT.</td>
</tr>
</tbody>
</table>
3.2 Software Used

A portion of this analysis is completed using data available through the International Research Institute Data Library (IRIDL). The IRIDL allows analysis using the built-in programming language Ingrid, which runs on Linux. Ingrid also allows for manipulation of large data sets, namely netCDF. Ingrid allows the user to read data directly from the data set and output calculations, models, and graphics, including maps and graphs. The correlation graphics included in this thesis are created using this software.

Data extraction, manipulation, and graphics creation were also performed using the R programming language, which is an open-source system designed for statistical computation and graphics. R was originally written by Ross Ihaka and Robert Gentleman at the Department of Statistics of the University of Auckland in New Zealand, but has grown with a core support staff as well as through user updates and package creation (R Core Team, 2016).
Chapter 4
Methods and Results

4.1 Determining LFR Data Distribution

First, the data are averaged per month, per grid cell over each data set. For each variable (LFR, SST, air temperature, specific humidity, u-wind, and v-wind) there are a total of 228 months in each data set, per grid cell. All levels of the troposphere are combined into one data set per variable (example: all v-wind recordings between 1000 mb – 200 mb are combined to a single data set). Each of these combined data sets are analyzed to determine the normality of the distributions using the Shapiro-Wilk test of normality. The formula for this test is as follows:

\[ W = \frac{\left( \sum_{i=1}^{n} a_i x(i) \right)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \]  

(4.1)

Where \( x(i) \) is the ith order statistic and \( \bar{x} = (x_1 + \cdots + x_n) / n \) is the sample mean; the constants \( a_i \) are given by the equation:

\[ (a_1, \ldots, a_n) = \frac{m^T V^{-1}}{(m^T V^{-1}V^{-1}m)^{1/2}} \]  

(4.2)

where \( m = (m_1, \ldots, m_n)^T \) and \( m_1, \ldots, m_n \) are the expected values of the order statistics of independent and identically distributed random variables sampled from the standard normal distribution, and \( V \) is the covariance matrix of those order (Sage, 2007).

A p-value \( \leq 0.05 \) indicates a non-normal distribution. Table 4.1 shows the results of the Shapiro-Wilk test for each dataset. The test confirmed non-normal distributions for each data set. 

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Table 4.1: Shapiro-Wilk test of normality. A p-value ≤ 0.05 indicates a non-normal distribution.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>W</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFR</td>
<td>0.93919</td>
<td>7.667e-08</td>
</tr>
<tr>
<td>SST</td>
<td>0.98718</td>
<td>0.04911</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>0.97584</td>
<td>0.047251</td>
</tr>
<tr>
<td>Specific Humidity</td>
<td>0.82129</td>
<td>0.037105</td>
</tr>
<tr>
<td>u-Wind</td>
<td>0.91278</td>
<td>0.048722</td>
</tr>
<tr>
<td>v-Wind</td>
<td>0.92718</td>
<td>0.0412574</td>
</tr>
</tbody>
</table>

Due to non-normal distributions, the data violate the assumptions of normality required of the Pearson correlation coefficient, therefore a Spearman’s rank correlation coefficient (Spearman’s rho) was chosen. Spearman’s rho is a non-parametric alternative to Pearson’s correlation and tests the level of dependence of two variables without requiring a linear relationship (Larsen, 2014).

Correlation tests are run to analyze relationships between the variables and LFR, which are explored in more depth. In Spearman’s rho, first the data are ranked, then they are run using the following equation:

$$ r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} $$  \hspace{1cm} (4.3)

In this equation, $\sum d$ is equal to $(x - y)$ where $x$ and $y$ are, for example, ranked SST and LFR monthly mean values and $n$ is equal to the number of ranked pairs (228 monthly pairs). The null hypothesis ($H_0$) states that no correlation exists between LFR and the independent variable. The alternate hypothesis ($H_1$) is that there exists a positive or negative correlation. Before correlation tests are run, a monthly climatology, using the 228 months, is created for LFR to determine seasonality. Based on the time-series in Figure 4.1, the data are compiled into annual and seasonal data sets. From these data sets correlation tests are run. LFR seasons are chosen to account for the wet/dry seasons and seasons of
high/low LFR (Figure 4.1. The breakdown is as follows: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), and September, October, November (SON).

![Graph showing monthly climatology for 228 months of LFR in the LMB (1996–2014)](image)

Figure 4.1: Monthly climatology for 228 months of LFR in the LMB (1996–2014)

Typically, in statistical testing a p-value of $\leq 0.05$ is considered significant, however, in the majority of this study a p-value of $\leq 0.1$ is used. This confidence interval is also considered significant, with a higher risk of error. It was chosen due to the nature of the study and intended use, which is to create a foundation of possible relationships between local and global climate on LFR in a region that has not been widely studied. Multiple climate variables are considered, at many levels of the atmosphere and at various spatial and temporal scales. As not to overlook any potential correlations that may exist between these variables at finer scales, a laxer p-value is chosen. Correlations revealed can then be analyzed in more precise manner in future studies. It is acknowledged that in any correlation study there is a chance of both Type I and Type II errors, these errors include false correlations and a failure to detect correlations, respectively. Each error type is considered when drawing physical connections to correlations and any claims of relationships between the variables are stated with caution. With a p-value threshold of $\leq 0.1$ there is a one-in-ten chance that an error will occur.
4.2 Correlations between LFR and SST

Annual correlations are conducted on a gridded scale, followed by the previously mentioned seasonal breakdowns. All grids colored are shown at significance level $\leq 0.1$. A positive correlation (red) suggests that with an increase (decrease) in SST, there should be an increase (decrease) in LFR. A negative correlation suggests that with an increase (decrease) in SST there should be a decrease (increase) in LFR in the LMB.

4.2.1 Annual Correlations

Figure 4.2 shows strong significant negative correlations in the Pacific Ocean on an annual scale. This suggests that when Pacific SST decreases anomalously, LFR in the LMB increases, or vice versa. When SSTs decrease on the eastern side of the Pacific, pressure gradients shift.

![Figure 4.2: Annual correlations between LFR and SST](image)

A high pressure will form over the cooler SSTs and create a circulation pattern in which divergence will occur on the eastern side of South America, including over the LMB. Divergence over the Pacific may enhance convergence over the LMB, which would lead to thunderstorm production and therefore LFR will decrease. A change in the normal Walker Circulation during a La Niña/El Niño phase may be responsible for the warming of SST in this region and may be responsible for the negative correlation to LFR. There are few
grid cells showing significant positive correlations in the Caribbean and tropical Atlantic, near Brazil. Positive correlations suggest when regional SST increases anomalously, LFR increase. Reasons for this could include increased SST leading to increased convection.

4.2.2 Seasonal Correlations

Seasonal correlations during DJF (Figure 4.3) show statistically significant positive and negative correlations. A negative correlation in the southern portion of the AMM region suggests that an anomalous decrease (increase) in SST will increase (decrease) LFR in the LMB. Influence of SST in this region could be due to shifts in pressure and therefore the speed and direction of the trade winds. When temperatures in the south Atlantic are anomalously cooler than those of the north Atlantic, air pressure above the SSTs will change, with low pressures over the warmer waters and high pressure over the cooler waters. The direction of flow will be more southerly, thereby weakening the northeasterly trades. This theory is supported by the positive correlations in u-wind found during DJF in the lower levels of the atmosphere (Figures 4.18a,b). The negative correlation may also be related to the negative correlations found near the east coast of Brazil in DJF for u wind (Figure 4.18) at 700 mb and between 600 mb and 200 mb for v wind (Figure 4.23), which may be due to a change in normal directional wind flow occurring during times of anomalous SST warming or cooling.

Figure 4.3: DJF correlations between LFR and SST
In the northern extent of the Caribbean, within the range of the AMM, there are strong positive correlations between SST and LFR. During this time, an anomalous decrease may have more influence on the production of LFR due to the already seasonally cooler SSTs. The positive correlation may suggest relationships between cooler than normal SSTs and corresponding decreased convection, and thus, decreased LFR.

In MAM (Figure 4.4), there is very little negative correlation in any of the ocean regions, but a very strong and widespread positive correlation in the Caribbean Sea. SSTs in the Caribbean begin to warm in March due to the expansion of the WHWP and continue through September. A rise in SST in the Caribbean coincides with a rise of LFR in LMB during this season. An anomalous increase of SST in the WHWM would presumably lead to increased LFR though temperature advection. The section of positive correlation west of Central America is also likely due to anomalous expansion of the WHWP, as it expands into this region between April and October.

During JJA (Figure 4.5), negative correlations are found in the Pacific Ocean. Similar to the relationship between the Pacific SST and LFR in LMB on an annual scale, when the temperatures of the eastern Pacific decrease, LFR increases, or vice versa and anomalous cooling (warming) would heighten this relationship. This correlation may suggest a rela-
tionship between shifting circulation patterns related to the Walker Circulation. During a strong Walker Circulation the temperatures may be cooler than normal and lead to high pressure over the equatorial Pacific while allowing convergence to increase over the LMB. The Walker Circulation patterns and ENSO events can be monitored via PDO and various Niño indices. The entire Caribbean, and portion of the western tropical Atlantic show a strong positive correlation. This is also likely due to the expansion of the WHWP and the influence of anomalous SST change in already warm waters.

![Figure 4.5: JJA correlations between LFR and SST](image)

SON has very few negative correlations (Figure 4.6). In the eastern Caribbean there are positive correlations moving into the North Atlantic and close to western Africa. The extent of the WHWP is still large in September and October and anomalous warming of the warm pool is likely the cause of these correlations. Warm temperatures in the tropical Atlantic are associated with the formation of strong tropical storms, including hurricanes, which may encourage instability and thunderstorm production in the LMB. Also, a small section of positive correlation in the Niño region of the Pacific Ocean suggest an increase (decrease) in SST in this region will increase (decrease) LFR. These correlations are likely due to Walker Circulation shifts and this region can be monitored using the Niño 4 climate index.
The most notable gridded correlations between LFR and SST occur in the WHWP region of the Caribbean Sea during spring and summer, the AMM region at all seasonal scales, and the Walker Circulation region in JJA and on an annual scale. To substantiate relationship claims between these climate variability patterns and LFR in the LMB, correlation tests are run using monthly climate indices. A number of climate indices are available that are intended to monitor and identify climate variability phases and patterns such as ENSO, WHWP and PDO. The climate indices chosen are as follows: 1- AMM (SST): records anomalous SST in the tropical Atlantic; 2- AMM (Wind): records wind anomalies over the tropical Atlantic; 3- Niño Monitoring region 3: records SST in the tropical Pacific and identifies ENSO phases; 4- ONI (Oceanic Monitoring Index) monitors SST anomalies in the tropical Pacific by using 5 consecutive 3 month SST anomalies of the Niño 3.4 index, currently the most common index used to identify ENSO phases; 5- PDO: measures SST anomalies of the northern Pacific Ocean; 6- SOI (Southern Oscillation Index) records pressure difference between Haiti and Darwin, Australia, this is the former most common index used to identify ENSO phases, 7- WHWP: measures SST anomalies in the Caribbean Sea and portions of the Atlantic Ocean.

All indices are statistically correlated to LFR on a monthly scale. Taking into consideration both the seasonal gridded correlations and the climate indices correlations, the
influence of the WHWP, the AMM wind anomalies, the PDO and the Niño 3.4 region (including ONI) appear to be the most influential on LFR in the LMB. These indices should be closely monitored when considering seasonal forecasting or uncharacteristic variability of LFR in the LMB.

Table 4.2: Climate Indicies: Shapiro-Wilk test of normality. A p-value ≤ 0.05 indicates a non-normal distribution.

<table>
<thead>
<tr>
<th>Index</th>
<th>rho</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMM (SST)</td>
<td>-0.104168</td>
<td>0.0127</td>
</tr>
<tr>
<td>AMM (Wind)</td>
<td>0.3281491</td>
<td>8.14E-07</td>
</tr>
<tr>
<td>ONI</td>
<td>0.1684421</td>
<td>0.01318</td>
</tr>
<tr>
<td>PDO</td>
<td>-0.1976302</td>
<td>0.00354</td>
</tr>
<tr>
<td>SOI</td>
<td>-0.1238484</td>
<td>0.06927</td>
</tr>
<tr>
<td>WHWP</td>
<td>0.3249544</td>
<td>1.05E-06</td>
</tr>
<tr>
<td>Nino 3.4</td>
<td>0.1938794</td>
<td>0.004291</td>
</tr>
</tbody>
</table>

4.3 Correlations between LFR and Temperature

Annual correlations are conducted on a gridded scale, followed by the previously mentioned seasonal breakdowns. All grids colored are shown at significance level ≤ 0.1. A positive correlation (green) suggests that when air temperature increases (decreases), LFR increases (decreases). Negative correlations (purple) suggest that an increase (decrease) in air temperature will be associated with a decrease (increase) in LFR in the LMB.

4.3.1 Annual Correlations

Figure 4.7 shows correlations between LFR and tropospheric temperature on an annual scale. Within the PBL from 1000 mb to 850 mb (Figure 4.7a-c) there are positive relationships over the Caribbean Sea, the Gulf of Mexico, and the northern tropical Atlantic. These correlations are consistent with the literature that states a rise in temperature near
the surface and lower levels of the atmosphere will increase LFR (Williams et al., 2005; Nath et al., 2009; Collier et al., 2012). On the 850 mb level (Figure 4.7c) there are also positive correlations over northeastern South America and portions of the Pacific Ocean. Warm air within the PBL should increase thunderstorm production, therefore increasing LFR. Between the 700 mb and 400 mb levels (Figure 4.7d-g) there are positive correlations over portions of Central America and the Gulf of Mexico. Between 400 mb and 200 mb (Figure 4.7g-j), there exist positive correlations in the northern extent of the tropical Atlantic. These positive correlations indicate that warmer air temperatures are linked to increased LFR, even slightly away from the LMB. The 200 mb level (Figure 4.7j) shows negative correlations over south of the LMB and the extent of the South America within the domain. This correlation is interesting because it is the only large negative correlation related to temperature. Since it is not found directly over the LMB, nor in any seasonal breakdowns, it cannot be explained at this time, but will be explored in future research.

4.3.2 Seasonal Correlations

Figure 4.8 depicts temperature correlations during DJF. Compared to the annual correlations, fewer grid cells display relationships. Low-mid tropospheric levels (Figures 4.8a-f) still show positive relationships to LFR, mainly over the Caribbean and Atlantic. There are weak or non-existent correlations in the upper troposphere (Figures 4.8g-j). Between the 700 mb and 500 mb levels (Figures 4.8d-f) are positive correlations in the Atlantic and negative relationships over the Gulf of Mexico (Figure 4.8 d-f). At the 700 mb (Figure 4.8d) level there is a small section of positive correlation to the south and west of the LMB and at the 250 mb level (Figure 4.8i) to the east of the LMB. The 200 mb (Figure 4.8j) level shows no correlation during this season, while there is a negative correlation on the annual scale. Temperature in DJF does not appear to be strongly related to LFR in the LMB. This is likely due to the influence of the dry season following the migration of the ITCZ. LFR in the area may be more related to moisture during this season than to temperature fluctuations.
Figure 4.9 shows temperature correlations during MAM. There are no negative correlations at any levels during this season. From 1000 mb to 700 mb (Figures 4.9a-d) positive correlations cover a large portion of the entire domain. Surface temperatures are important in the production of thunderstorms and temperatures begin to climb in spring over the LMB. In the middle troposphere, between 600 mb and 400 mb (Figures 4.9e-g) the positive correlations are no longer over the continent, but still remain over the Pacific and Atlantic. The reasons for these correlations are not yet understood, but may be due in part to thermal advection. In the upper troposphere (Figures 4.9f-i), the positive correlations return to cover a large portion of the domain until the 200 mb level (Figure 4.9j) where there is only a small correlation over the Gulf of Mexico. With the exception of the middle troposphere, positive correlations are found over the extent of South America, including the LMB. This is consistent with the literature that suggests an increase in temperatures is linked to an increase in LFR (Williams et al., 2005; Nath et al., 2009; Collier et al., 2012).

Figure 4.10 depicts temperature correlations during JJA. Similar to MAM, there are no negative correlations and positive correlations are found at every level. Between 1000 mb and 700 mb (Figures 4.10a-d) a large portion of the domain show positive correlations, including the Atlantic Ocean and Caribbean Sea. Between 600 mb and 500 mb (Figures 4.10e-f) the positive correlations are over the Caribbean Sea and between 400 mb and 200 mb (Figures 4.10 g-j) they are found over the Atlantic. The influence of the warm air from the Caribbean is likely responsible for these correlations. The 300 mb level (Figure 4.10h) shows positive correlations over a large extent of the domain. At the 250 mb and 200 mb levels (Figures 4.10i-j) there are positive correlations over the Gulf of Mexico and Atlantic Ocean, as well as over the Caribbean Sea at 250 mb. The vertical extent of the troposphere increases when a column of air remains warm at higher levels. An extended troposphere is known to be important in the production of thunderstorms (Sátori et al., 2009).

Figure 4.11 shows temperature correlations during SON. Similar to JJA and MAM there are no negative correlations at any levels. The 700 mb (Figure 4.11d) shows very
small areas of positive correlations over the Atlantic, 500 mb - 200 mb (Figures 4.11f-j) show correlations over the Atlantic which may be due in part to warm air advection flowing from warm SST into South America. The 400 mb – 300 mb levels (Figures 4.11g-h) have correlations in parts of the Caribbean Sea. Compared to the warmer seasons of MAM and JJA, there are fewer correlations in SON and those that do exist are confined to a small section of the Atlantic Caribbean. This is likely due to the cooler temperatures of the fall season.

Aside from on an annual scale and the cooler/dry season of DJF, it appears that temperature from low to middle tropospheric levels is positively correlated to LFR in the LMB, which means when temperature increases so does LFR and when temperature decreases, LFR should decrease as well. Extensive correlations were found over the northern portion of South America, the tropical North Atlantic, the Caribbean Sea, and the Gulf of Mexico. It appears that warmer, wetter seasons have stronger relationships between temperature and LFR than do cooler, drier seasons. Further research could explore the negative correlation at the 200 mb level on an annual scale (Figure 4.7j).
Figure 4.7: Annual correlations between LFR and temperature
Figure 4.8: DJF correlations between LFR and temperature
Figure 4.9: MAM correlations between LFR and temperature
Figure 4.10: JJA correlations between LFR and temperature
Figure 4.11: SON correlations between LFR and temperature
4.4 Correlations between LFR and Specific Humidity

Annual correlations are conducted on a gridded scale, followed by the previously mentioned seasonal breakdowns. All grids colored are shown at significance level $\leq 0.1$. A positive correlation (green) suggests that when specific humidity increases (decreases), LFR should increase (decrease). Negative correlations (purple) suggest that an increase (decrease) in specific humidity should be linked to a decrease (increase) in LFR.

4.4.1 Annual Correlations

Figure 4.12 shows correlations between LFR and specific humidity on an annual scale. The surface and 925 mb level (Figures 4.12 a,b) show sporadic positive correlations over South America, concentrated over the delta in Brazil and negative correlations over the Atlantic northeast over Puerto Rico and Cuba. Negative correlations over the coast may be due to anomalous divergence and convergence of the Walker Circulation that spark a change in precipitation patterns in northern South America. The 925 mb level (Figure 4.12b) also has positive correlations in the tropical north Atlantic. The 850 mb level (Figure 4.12c) show negative correlations in the northern extent of the Caribbean Sea. Between 700 mb and 400 mb and a smaller section at the 300 mb level (Figures 4.12d-h) are positive correlations over the center of and west coast of South America. There is a negative correlation over a portion over Central America at the 300 mb level (Figure 4.12h). Wherever specific humidity increases, the air is closer to saturation, and thus, encourages thunderstorm production. More insight is offered in the seasonal breakdowns.

4.4.2 Seasonal Correlations

Figure 4.13 shows correlations during DJF. The 1000 mb and 925 mb levels (Figures 4.13a,b) show positive correlations north of the LMB over the Caribbean Sea and over Cuba and Puerto Rico from the surface to the 400 mb level (Figures 4.13a-g). Moisture near the Caribbean can be blown into the LMB, so an increase (decrease) in moisture over that region should contribute to an increase (decrease) of LFR as it has been shown to
be connected to moisture. A positive correlations is also found over the northern tropical Atlantic at the 300 mb level. Negative correlations are more prevalent during this season than on an annual scale and are mainly concentrated in the Atlantic east of northern South America between 925 mb and 400 mb (Figures 4.13d-g). These inverse relationships may indicate a connection between weather in northern Venezuela and precipitation regimes near the coast of Brazil.

Figure 4.14 shows correlations during MAM. Positive correlations are dominant and extensive between the surface and 500 mb (Figure 4.14a-f). The correlations extend over the center of South America and over the Pacific west of Ecuador as well as over the Atlantic east of Puerto Rico and Cuba. Positive correlations also exist in portions of the Caribbean Sea at the 1000 mb, 700 mb and 600 mb levels (Figures 4.14a,d,e) Similar to DJF, negative correlations are found to the east of South America at levels between 700 mb and 300 mb (Figures 4.14c-h) and appear to congregate near the delta near the coast of Brazil.

Figure 4.15 shows correlations for JJA. Between the surface and the 850 mb level (Figures 4.15a-c) show positive correlations over the center of South America. Positive correlations are also apparent over the northern tropical Atlantic at the 1000 mb (Figure 4.15a) and between the 850 mb and 700 mb levels (Figures 4.15c-f). The surface also shows extensive correlations in the Atlantic and the Caribbean Sea. Negative correlations are found near the delta of Brazil, with the most extensive being at the 400 mb and 300 mb levels. These negative correlations go against the literature, which states that LFR is enhanced during the wet seasons.

Figure 4.16 shows correlations for SON. There are positive correlations east of Puerto Rico and Cuba from 1000 mb to 850 mb (Figure 4.16a-c). Negative correlations are found over the southern extent of Central America between the surface and 700 mb (Figures 4.16a-d). There is a notable negative correlation at the 400 mb and 300 mb levels (Figure 4.16g) over northeastern South America extending into a small portion of the Atlantic.
These are similar to the correlations during the other seasons. In general, correlations are less extensive in SON than in other seasons.

The most widespread negative and positive correlations were found in the warm seasons of MAM and JJA. Most positive correlations are found over the center of South America and the tropical Atlantic. The majority of negative correlations are found over the Atlantic and near the delta of Brazil. Weather in northern South America may be tied with the climate and precipitation regimes of eastern Brazil and is of particular interest. Considering relationships to the MJO and SAL would be of interest in future research as correlations between moisture and LFR are apparent. Many correlations between LFR and the other variables are found in this area and further research is necessary.
Figure 4.12: Annual correlations between LFR and specific humidity
Figure 4.13: DJF correlations between LFR and specific humidity
Figure 4.14: MAM correlations between LFR and specific humidity
Figure 4.15: JJA correlations between LFR and specific humidity
Figure 4.16: SON correlations between LFR and specific humidity
4.5 Correlations between LFR and u-wind

Annual correlations are conducted on a gridded scale, followed by the previously mentioned seasonal breakdowns. All grids colored are shown at significance level $\leq 0.1$. U-wind is the zonal wind (west to east) and is measured in meters per second. A negative measurement of u-wind indicates that the wind has an east to west component of motion. Positive correlations (green) suggests that an increase in speed in a positive u-wind is linked to an increase in LFR and a decrease in speed in a positive u-wind (or a reversal in direction) will decrease LFR in the LMB. A negative correlation (purple) suggests that an increase in speed in a positive u-wind has lower LFR and a decrease in speed in a positive wind (or reversal of direction) has an increased LFR.

4.5.1 Annual Correlations

Figure 4.17 shows u-wind correlations on an annual scale. Positive correlations are found between 1000 mb and 850 mb (Figures 4.17a-c) over western South America and extending into the Pacific. From 925 mb to 600 mb (Figures 4.17b-e) there are only positive correlations. Correlations are found at the 700 mb level (Figure 4.17d) near the center of South America and west of the LMB and at 600 mb (Figure 4.17e) in the center of the continent. The Pacific also displays a negative correlation between the 600 mb and 400 mb levels (Figures 4.17e-g). Levels between 500 mb and 200 mb (Figures 4.17f-j) only show negative correlations. At 200 mb and 300 mb (Figures 4.17h,j) in central and western South America, extending slightly into the Pacific. Reasons are explored in detail in the seasonal breakdowns.

4.5.2 Seasonal Correlations

Figure 4.18 shows correlations during DJF. Between 1000 mb and 400 mb (Figures 4.18a-g) positive correlations are found over the Caribbean, Central America, and the western tropical Atlantic, increasing in extent toward the surface. Negative correlations are found over central South America between the surface and 500 mb (Figures 4.18a-f).
These negative relationships may be due to wind shear in the mid-troposphere and upper levels. There are positive correlations in the center of South America extending into the Atlantic between 300 mb and 200 mb (Figures 4.18h-j). More westerly winds could increase wind flow into the LMB and enhance upper-level divergence and surface convergence.

Figure 4.19 shows positive correlations during MAM at all levels of the troposphere over tropical north Atlantic and the Caribbean, increasing with a decrease in height, until the 925 mb (Figure 4.19b) where it begins to weaken. Though these correlations do not appear directly over the LMB, temperature and moisture advection may be the reason for the correlations. Correlations are found in areas that are known to supply the LMB with much of its heat and moisture and may be important within the cooler, drier months of DJF. There are negative correlations over a small section of the Atlantic near a delta in northeastern Brazil between the surface and 400 mb (Figures 4.19a-g).

Figure 4.20 shows JJA shows positive correlations throughout the extent of the troposphere up to 400 mb (Figures 4.20a-g). Positive relationships over the basin are consistent with the literature, as temperature and moisture advection in the u wind is crucial in the development of thunderstorms in the LMB. Between 300 mb and 200 mb (Figures 4.2h-j) there are negative relationships just north and east of the LMB, increasing with height. According to Zhu and Stan (2014), there is an increase in vertical wind shear near the 250 mb – 200 mb level over the western tropical Atlantic during a positive AMM phase and El Niño. Also during El Niño years, the Walker Circulation triggers UL westerly anomalies over the tropical Atlantic.

Figure 4.21 shows correlations during SON. Between the surface and 925 mb (Figures 4.21a-b) the correlations over the Atlantic are farther west near the Caribbean and over Puerto Rico and Cuba, as well as directly over the LMB. Below the 600 mb level (Figures 4.21a-e), there is little to no negative correlation. Positive correlations are found between the surface and 600 mb (Figures 4.21a-e) over the center of northern South America portions of the eastern tropical Pacific and western tropical Atlantic. There are negative correlations
between 500 mb and 400 mb (Figures 4.21f-g) over a portion of the eastern tropical Pacific. There are all negative correlations between 400 mb and 200 mb (Figures 4.21g-j) over a large extent east of LMB, extending into the Atlantic. The negative correlations found between 300 mb and 200 mb (Figures 4.21h-j) are of interest and will be explored further. The positive correlation are consistent with the literature and should be explored on a finer temporal resolution when considering seasonal forecasting.
Figure 4.17: Annual correlations between LFR and u-wind
Figure 4.18: DJF correlations between LFR and u-wind
Figure 4.19: MAM correlations between LFR and u-wind
Figure 4.20: JJA correlations between LFR and u-wind
Figure 4.21: SON correlation between LFR and u-wind
4.6 Correlations between LFR and v-Wind

Annual correlations are conducted on a gridded scale, followed by the previously mentioned seasonal breakdowns. All grids colored are shown at significance level $\leq 0.1$. V-wind is the meridional wind (south to north) and is measured in meters per second. A negative measurement of v-wind indicates that the wind has a north to south component of motion. Positive correlations (green) suggest that an increase in speed in a positive v-wind is linked to an increase in LFR and a decrease in speed in a positive v-wind (or a reversal in direction) is associated with a decrease in LFR in the LMB. A negative correlation (purple) suggests that an increase in speed in a positive v-wind is linked to decreased LFR and a decrease in speed in a positive v-wind (or reversal of direction) is tied to increased LFR.

4.6.1 Annual Correlations

Figure 4.22 shows annual correlations for v-wind. Positive correlations are found directly over the LMB at the surface and 925 mb level (Figures 4.22a-b) and in the western tropical Atlantic at all levels. These correlations suggest that an increase (decrease) in the strength of a southerly wind (negative wind) is related to an increase (decrease) in LFR. This is interesting because LFR in LMB is typically closely tied with the northerly NLLJ that flows from the Caribbean into the LMB most nights. The negative correlations could be due to the descent of the cooler katabaic winds from the Andes mountains. Negative correlations are also found at all levels, they are found in the Pacific in the upper-troposphere and decreasing in extent closer to the surface. Negative correlations indicate that (FIX)

4.6.2 Seasonal Correlations

Figure 4.23 shows that positive relationships are found over portions of the Caribbean between the surface and 600 mb (Figures 4.23a-e) as well as over the LMB and part of northern South America between the surface and 500 mb (Figure 4.23a-f) during DJF. Typically the NJJL brings warm, moist air from Caribbean Sea and Atlantic which help increase the formation of thunderstorms. A shift to positive v-winds during DJF may be
due to relatively cooler temperatures in the basin encouraging the thermal descent of cooler air from the Andes mountains. The air will meet warmer moist air over the basin creating convection and thunderstorm development. There are negative correlations between 400 mb – 200 mb (Figures 4.23g-j) east and west of South America, along the coast in Pacific and Atlantic Oceans during the DJF season. Negative correlations are also found east of northern Brazil over the Atlantic.

Figure 4.24 suggests that negative correlations are not as well defined in MAM as they are in DJF. Between the surface and 700 mb (Figure 4.24a-d) in portions of northern South America show negative correlations. Negative correlations are also found over the delta in northeastern Brazil between the surface and 400 mb (Figure 4.24a-g). Positive correlations are found over the LMB between 850 mb and 500 mb (Figure 4.24c-f), as well over the western Atlantic between the surface and 925 mb (Figure 4.24a-b) and over the Caribbean between 700 mb and 200 mb (Figure 4.24d-j).

Figure 4.25 shows that at the 1000 mb to 850 mb (Figures 4.25a-c) levels are positive correlations directly over the LMB. The 700 mb to 500 mb levels (Figures 4.25d-f) show correlations over the Caribbean and the Pacific and are sporadic from 500 mb to 200 mb level (Figures 4.25f-j) where they become more extensive. Negative correlations are found over the Pacific at 925 mb and 850 mb (Figures 4.25b-c) as well as over the northern portion of South America from the surface to 850 mb (Figures 4.25a-c). They are also found to the east of the LMB at 500 mb (Figures 4.25f) over the Pacific and near the west coast of South America at the 300 mb and 250 mb levels (Figures 4.25h-i). Wind patterns over western South America may be tied with larger-scale circulation that affects weather in the LMB. These correlations appear frequently during JJA in all variables, with the exception of temperature.

Figure 4.26 shows v-wind correlations during SON. Positive correlations are minimal at all levels, but at the surface and 925 mb levels (Figures 4.25a-b) there are positive relationships in the western Atlantic. Between 400 mb and 200 mb (Figures 4.25g-j) there
are small sections of positive correlations near the delta in northeastern Brazil. Negative correlations are better defined. Between the surface and the 400 mb level (Figures 4.25a-g) they are concentrated over the Gulf of Mexico and the Caribbean. From the surface there are also negative correlations from the surface to the 850 mb (Figures 4.25a-c), as well as 300 mb level (Figures 4.25h) over the west coast of South America, extending into the Pacific.

Negative correlations within the PBL may be due in part to thermal advection. Meridional winds in the area are typically associated with the NLLJ that blows from the north bringing warm, moist air from the Caribbean and provide thunderstorms with energy. If an air mass moves in with a temperature lower than the surface temperature of land, the moving air mass will remove the heat from the region. The positive correlations within the PBL near the LMB and Caribbean Sea may be due to the onshore breeze and NLLJ which bring moisture and instability into the region. In one study, it was found that there are positive relationships between LFR and the NLLJ maxima and negative relationships with the CLLJ maxima (Muñoz and Díaz-Lobatón, August 8-10, 2011). Wind shear in the upper levels may be responsible for both positive and negative relationships. Removal of ascending air at the top of a storm will enhance it, while shear in the middle atmosphere may weaken the storm by breaking it apart.
Figure 4.22: Annual correlations between LFR and v-wind
Figure 4.23: DJF correlations between LFR and v-wind
Figure 4.24: MAM correlations between LFR and v-wind
Figure 4.25: JJA correlations between LFR and v-wind
Figure 4.26: SON correlations between LFR and v-wind
Though correlation tests between LFR and the dependent variables were run and described independently from one another, these variables are not separate entities in the climate system and many correlations are undoubtedly tied to, and influenced by each other. Anomalous changes in SST can impact atmospheric flow in a number of ways, including changing direction and speed of wind, which itself transports heat and moisture. Air temperatures can affect moisture content and evaporation processes as well as influence wind flow and pressure patterns. Humidity can alter temperatures in air masses that can affect SSTs. Wind speed and direction (zonal and meridional) can influence SSTs by transporting air masses of different temperatures over oceans, changing SSTs through evaporation and precipitation. These are just limited examples of inter-connectivity of variables in the climate system.

In the gridded correlations, the most common connected variables are temperature and humidity, most notably in the warmer/wetter seasons and within the planetary boundary layer. These connections are not surprising as heat and moisture directly facilitate thunderstorm production. U-wind during MAM appears to be closely connected to temperature between 1000 mb and 700 mb over the Caribbean Sea, likely due to the advection of heat from the high SSTs. During JJA all of the variables appear to be connected directly over the LMB at the surface as zonal and meridional winds bring warm, moist air into the basin. During SON u-wind and temperature appear to be connected to the east of the LMB at the upper levels of the atmosphere. Many connections between the variables can be drawn and can be analyzed in a future study with a more narrow scope.
Chapter 5
Conclusions and Future Research

5.1 Conclusion

Lightning strikes are the second most dangerous natural hazard to humans. Research of LFR has vastly improved over the last two decades and LFR is now predictable on time scales as short as seasonal. However, single flashes are still unpredictable. Understanding lightning occurrence and LFR can help reduce death, injury, and economic loss by increasing public consciousness and improving mitigation planning.

Lightning occurs on every continent, but the majority occurs within the tropical climate region. Tropical northern Venezuela is home to a set of recurring lightning storms, named “Catatumbo Lightning” that produce the most lightning flashes in the world. Past studies have revealed that the topography and geography of the Catatumbo region are an important contributing factor to the localized production of Catatumbo Lightning. LFR has been directly linked to temperature and precipitation, which are influenced by global and localized climate drivers. Climate drivers that have the potential to affect the weather of northern Venezuela are SST, the Walker Circulation, ENSO, PDO, MJO, AMO, AMM, WHWP, ITCZ, CLLJ, NLLJ, trade wind inversions, TUTT, and the SAL. Fluctuations in the patterns of these drivers may be responsible for variation in LFR across the globe. This thesis analyzed correlations between LFR and SST and between LFR and tropospheric air elements.

Lightning data used in this study come from merged LIS/OTD data sets beginning January 1998. These data are on a 2.5° x 2.5° scale. The SST data used are NOAA OI.v2 SST (NOAA/OAR/ESRL PSD). These data are obtained by readings from ships and buoys on a 1°x1° grid and averaged onto a monthly time scale. The SST domain was chosen to encompass the AMM region of the Atlantic, the entire Niño monitoring region of the Pacific, and the entire Caribbean Sea. Tropospheric air data were taken
from NOAA’s NCEP/NCAR Reanalysis I. Four variables were considered: temperature, specific humidity, u-wind velocity (zonal wind) and v-wind velocity (meridional wind). Each variable is measured at various pre-defined barometric pressure levels as denoted by the AMS (1000 mb, 925 mb, 850 mb, 700 mb, 600 mb, 500 mb, 400 mb, 300 mb, 250 mb, and 200 mb. Specific humidity is only available through 300 mb.). These data are on a 2.5°x2.5° grid and are the same spatial resolution as LFR and SST (January 1998 – December 2014). In this analysis the LFR data from the LMB from each grid point are averaged into a single monthly mean, per year. For 19 years of data and 12 months per year the LMB has 228 SST values. SST and tropospheric air variables are also averaged into monthly means.

After determining that the data were non-parametric, Spearman Rank correlation tests were run to identify relationships between LFR and SST and between LFR and tropospheric air elements. Positive and negative correlations were found during all seasons for SST as well as for all levels of the atmosphere. The extent and strength of the correlations vary. Some notable correlations are strong positive correlations in the Caribbean Sea during the height of the WHWP during March–August, substantiated by correlations between LFR and WHWP climate index. A negative correlation in u-wind was found over the western tropical Atlantic at the 200 mb level in agreement with Zhu and Stan (2014), who found that an anomalous wind during El Niño years creates a shear that suppresses thunderstorm growth. Many negative correlations were found in all variables over a small area of coastal Brazil, with the exception of temperature.

Some limitations to this research are that there are a limited number of complete observing years (1998–2014) and coarse spatiotemporal resolution. When considering annual and multi-decadal climate variability and fluctuation patterns such as the PDO, MJO, AMO, and ENSO it would be necessary to have many more complete years of data. Finer resolution studies should be conducted to better attribute wind flow patterns to LFR in
the LMB. A narrower scope would be beneficial to this specific research as well as to its contribution to lightning research in general.

The study of lightning in the most lightning-prone region in the world will advance the understanding of global and local climate drivers on lightning production in the tropics. Advancement in knowledge of the workings of the climate and weather in the tropics are important for the livelihood of those who reside in lightning-prone areas.

5.2 Future Work

Future work will entail analyzing relationships between SST and LFR using higher spatial and temporal resolutions as well as looking at hourly wind flow patterns. Some interesting studies may include further analyzing the 200 mb wind shear and flow patterns of u and v winds. Another future study may include analyzing connections between air flow near the delta in Brazil and LMB, including specific humidity and u and v wind as there were many correlations concentrated in that small region. Also, once a sufficient number of observing years for LFR exist, examination of SST patterns in relation to ENSO and other climate variability will be useful to provide insight to how LFR reacts to shifts in weather and climate patterns. Ultimately, the best way to research this phenomenon will be to install ground-based lightning sensors, in addition to a full-range weather station in the LMB.
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