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An analysis of the effects of climatic oscillations and hurricane intensification on the destructiveness of Gulf Coast hurricane landfalls

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By

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An analysis of the effects of climatic oscillations and hurricane intensification on the destructiveness of Gulf Coast hurricane landfalls

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Hurricanes are the leading cause of economic loss in the United States, and recent studies have shown that they have increased in intensity. The growth of population and wealth to coastal regions has exacerbated catastrophic losses. The purpose of this study is to examine the role of three modes of natural climate variability as well as hurricane intensification on destructiveness along the Gulf Coast. The study utilized R programming software to create raster grids and evaluate spatial and temporal relationships between intensification, intensity, sea surface temperatures and destructiveness. Destructiveness was synthesized using the Pielke Landsea 2018 (PL18) normalized losses dataset. The principal findings revealed that the Atlantic Multidecadal Oscillation (AMO) has the greatest influence on hurricane intensification and associated damages. The study offers a contribution to research on hurricane intensification and destructiveness associated with natural climate variability and urges stakeholders to dedicate funds for mitigation measures to reduce the vulnerability to Gulf Coast counties.

DEDICATION

This thesis is dedicated to my husband, Richard Vela.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor, Dr. Erik Fraza for taking on this task in advising me through this research. I truly cannot thank him enough for the time he spent coding to create the wonderful grids and statistical tests that were used in this study. Without his expert knowledge and coding in R, I would not have been able to conduct this research as thoroughly. I am extremely grateful for the time he spent working with me on my writing, explaining concepts and processes beyond my scope of knowledge, and being ever so patient with my countless questions each week. I have learned so much from Dr. Fraza and am forever grateful for the experience I had working with him. Next, I would like to thank my committee members, Dr. Chris Fuhrmann, Dr. Kathy Sherman-Morris, and Dr. Christa Haney for assisting and supporting me in this research. Each of your courses sparked a deeper passion inside of me on the relationship between climate/environmental science and society and were a major contributing factor in the decision to do a thesis on this topic. Thank you for your guidance and feedback. Finally, I would like to thank my family for their support during this journey. Specifically, I would like to thank my parents, Gary and Denise. I would not be here without their endless love, support and encouragement throughout my entire education. I am eternally grateful for all they have done for me to get here today. Finally, I would like to thank my husband, Richard. I would not have been able to complete this program without his unfailing support and encouragement each day. Thank you, from the bottom of my heart, for never letting me give up on myself and being the biggest supporter these past few years.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

The growth and development along the Gulf Coast over the last century have brought attention to the economic hardships and vulnerability that result from hurricanes that strike the region. While hurricane tracking has certainly improved, there is still a critical need to expand research concerning the destructive potential of these storms (Rappaport et al., 2010). According to the National Climate Assessment, the intensity and frequency of major hurricanes (Category 3-5) in the North Atlantic have increased substantially in the last three decades (Melillo et al., 2014). The amplification of hurricanes has sparked a debate surrounding anthropogenic influence. However, the purpose of this thesis is not to solve the debate around our human role in hurricane intensification. Rather, the objectives are to assess the magnitude to which hurricanes have intensified, evaluate the destructiveness that results from landfalls, and understand some of the climatological factors that influence intensification. More specifically, the focus on intensification and destructiveness will pertain to the Gulf of Mexico during the period 1900 to 2017.

Of all weather and climate disasters, hurricanes are the leading cause of economic damage in the United States (Klotzbach et al., 2018). According to Weinkle et al. (2018), the adjusted economic losses from hurricanes has averaged approximately $16.7 billion annually since 1900. Most damage from hurricanes is flood-related, and state-level data from the Federal

Emergency Management Agency (FEMA) indicates that the number of National Flood Insurance Program (NFIP) policies inflate following major events (Klotzbach et al., 2018). The NFIP is an affordable insurance program to property owners and renters which promotes not only the purchase of flood insurance but encourages communities to adopt floodplain management regulations to reduce the socio-economic impact of disasters (FEMA, 2019). The Gulf Coast alone has received over 60%, or $34.5 billion, of all NFIP payouts (Klotzbach et al., 2018). However, Deryugina (2017) argued that the fiscal costs of hurricanes are expected to rise due to population growth and climate change. As people migrate to coastal counties around the nation, insurance companies and government agencies have grown concerned with greater exposure and vulnerability to hurricanes due to their extensive economic impacts (Klotzbach et al., 2018). Particularly, this includes the rebuilding of infrastructure, along with unemployment insurance payments, public medical spending, and negative impacts to the local economy that rely on tourism, farming, transportation and other business sectors. While the contribution of human and natural causes pertaining to hurricane intensification rates is still not certain, Emanuel (2005) asserted that "...[F]uture warming may lead to an upward trend in tropical cyclone destructive potential, and- considering an increasing population- a substantial increase in hurricane-related losses in the twenty-first century."

Two-thirds of all hurricane landfalls in the continental United States occur along the Gulf Coast (Rappaport et al., 2010) where approximately 60 million people live (Klotzbach et al., 2018). Additionally, 20% of all hurricanes that strike the United States are major hurricanes that cause over 80% of the damage (Goldenberg et al., 2001). Thus, given a densely populated Gulf Coast region combined with stronger hurricanes making landfall, it is likely that the economic and social turmoil will continue to be of significance for the foreseeable future. Goldenberg et al. (2001) argued that, "Government officials should be aware of the shift in climate and evaluate preparedness and mitigation efforts needed to respond appropriately in a regime where hurricane threat is more prominent." For these reasons, it is imperative to analyze the magnitude of hurricane intensification in the Gulf of Mexico and the associated destructiveness to better forecast and lessen the fiscal burden that results.

Changes in SSTs due to human activities and natural climate variations have brought attention to the observed trends of the intensification of hurricanes during the time frame of this study. Although scientists may not yet be able to detect human impact[s], it is likely that hurricane intensification rates will continue to increase as long as anthropogenic influences persist. Additionally, the growth in population and wealth along the Gulf Coast means losses will continue to be of considerable magnitude for the foreseeable future. Therefore, a better understanding of hurricane intensification is critical for many stakeholders to work on mitigating the economic and social impacts from these destructive storms. Climatological changes that result from natural modes of climate variability occur on frequencies of 1-100 years. The three teleconnections contained in this work are the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO). This analysis will serve as valuable predictor to the destructive potential of tropical storms that are sensitive to the relative phases of each teleconnection, which will provide stakeholders with a better understanding of the climatological variables that contribute to the likelihood of higher frequency landfall years. The purpose of this research is to investigate the degree of intensification from 1900-2017 in the Gulf of Mexico, the relationship between intensification and each teleconnection that has shown to have an effect on Atlantic hurricane activity, and the relationship between destructiveness and each teleconnection.

Literature Review

Hurricane intensity is measured by the maximum 1-minute average, sustained near-surface (10 m) wind speed (Rappaport et al., 2010). As a storm extracts heat from warm tropical waters, it is converted into kinetic energy, or wind, (Judt, 2017) which is used to measure a hurricane's intensity on the Saffir-Simpson Hurricane Scale (National Weather Service, n.d.). Intensification is the positive change in the intensity of a tropical cyclone with time. Using a spatial framework developed by Elsner et al. (2012), which consists of equal area hexagon grids on a Lambert conformal conic projection, Fraza and Elsner (2013) found the region with the highest mean intensification was in the Gulf of Mexico. Still, as hurricanes increase in frequency and intensity (Melillo et al., 2014), there is an obligation for stakeholders to determine the best mitigation strategies to prevent and reduce catastrophic losses and extensive costs that result (Emanuel, 2005).

Understanding possible shifts in tropical cyclone genesis and intensification in a changing climate remains a high priority from both scientific and socio-economic viewpoints. In accordance with multiple studies, a rise in North Atlantic sea surface temperatures (SSTs) is the leading argument for hurricane intensification (i.e. Fraza & Elsner, 2015; Goldenberg et al., 2001; Wang et al., 2008). Holland and Webster (2007) stated that the trend in increasing SSTs exceeding +0.7°C and hurricane frequency is influenced by greenhouse warming. However, National Oceanic and Atmospheric Administration (NOAA) scientists argue that it is too early to conclude that human activities have already had a detectable impact on Atlantic hurricane activity (Geophysical Fluid Dynamics Laboratory, 2019). A sensitivity experiment by Semmler et al. (2008) found that a 1 K increase in SST and atmospheric temperature leads to an increased frequency and intensity of tropical cyclones over the North Atlantic. Additionally, Trepanier et al. (2015) found that rising SSTs will lead to an increased average power for hurricanes using the Maximum Potential Intensity (MPI) equation. In the North Atlantic, almost 55% of all hurricanes and 80% of all major hurricanes develop from tropical storms in the main development region (MDR), which form during the peak months of August through October (Bell & Chelliah, 2005). Additionally, tropical multidecadal modes are shown to link fluctuations in Atlantic hurricane activity which result from oceanic and atmospheric conditions (Bell & Chelliah, 2005). For example, La Nina years associated with the ENSO cycle contribute to increased numbers of hurricanes and hurricane losses as a result of decreased wind shear, weakened westerly winds, and SSTs that are $\geq 0.4°C$ cooler than the long-term average in the equatorial Pacific, known as Nino 3.4 region (Pielke & Landsea, 1999).

While SSTs play a critical role in the genesis, intensity, and intensification of hurricanes, Fraza & Elsner (2015) explained that vertical wind shear also affects intensity and power dissipation index (PDI), where the PDI is a measure of the total energy consumption by tropical cyclones (Emanuel, 2007). Wind shear refers to a change in wind speed and direction, which is argued to be the most critical factor in hurricane formation and destruction (Gray, 1968). Wind shear impairs tropical cyclones by removing the heat and moisture they need. Additionally, shear distorts the shape of the hurricane by blowing the top away, causing it to tilt and making it less efficient at drawing in warm, moist air from the surrounding ocean (Pritchard, 2016). According to Gray (1968), a general rule of thumb is that shear must be less than 20 knots (~ 10 m s^{-1}) for intensification to occur. Frank & Ritchie (2001) found that weak shear of 5 m s^{-1} or less allows a storm to remain vertically aligned and as a result, it could intensify for up to 36 hours before weakening. Although it is beyond the scope of this study to examine the effects of wind shear on hurricane intensification, it is necessary to briefly acknowledge the effects this variable has on the cyclogenesis of hurricanes.

Population Growth

The growth in population along the U.S. Coast has been identified as a contributing factor for the substantial economic losses that result after hurricane landfalls. The increase in population and housing of Gulf Coast counties affected by each hurricane in the study period is shown in Table 1 of the Appendix using data provided by Weinkle et al. (2018). In general, the population of the Gulf Coast counties that have been struck by a hurricane over the study period has increased 135%, from approximately 44.8 million in 1900 to 105.5 million in 2017. The average number of housing units in the Gulf Coast counties that have been struck by a hurricane over the study period has increased 161%, from approximately 18.2 million housing units in 1900 to 47.6 million in 2017. While it is difficult to get a thorough representation of the increase in population of all possible Gulf Coast counties that are susceptible to hurricane landfalls, this data provides a substantial overview of population and housing growth within the study area. If this growth continues, the potential for economic losses will be calamitous. The extreme development of vulnerable Gulf Coast counties that have endured the calamities of hurricane landfalls, reveals the importance in mitigating future losses through a combination of coastal engineering, building codes and zoning ordinances.

In addition to the growth in population along the Gulf Coast, Pielke et al. (2008) found that the trend in hurricane losses will continue to increase as wealthier people inhabit vulnerable regions. As wealth accumulates in susceptible Gulf Coast counties, the potential for catastrophic losses rises. According to one model by Pielke (2007), it is assumed that in 2050 the combined global population and wealth in locations vulnerable to hurricanes will be 7 times greater than they were in 2006. Individual wealth data are not feasible to obtain when considering all physical and intangible assets minus all debts. Thus, a common way to look at wealth has been to use gross domestic product, or GDP. GDP is the total market value of the goods and services produced within a country in a year (Bureau of Economic Analysis, 2019a). Using this method is limited by the fact that it does not encompass the stock of capital assets; however, it is a good starting point for measuring wealth (Mumford, 2016). To examine the effects of hurricane damage to this measure of wealth, the GDP by state for the Gulf Coast states was obtained from the Bureau of Economic Analysis (BEA) back to 1963 (Bureau of Economic Analysis, 2019b). GDP by state is unavailable before this year, which limits the findings. The base-economic damages from each hurricane was divided by the state(s) GDP the year it made landfall to get a percent that the hurricane damage represented (Figure 1.1). This method has been done by Pielke (2015) to consider U.S. flood damage as a percentage of U.S. GDP. Base-economic damages can be seen in Table 2 of the Appendix.

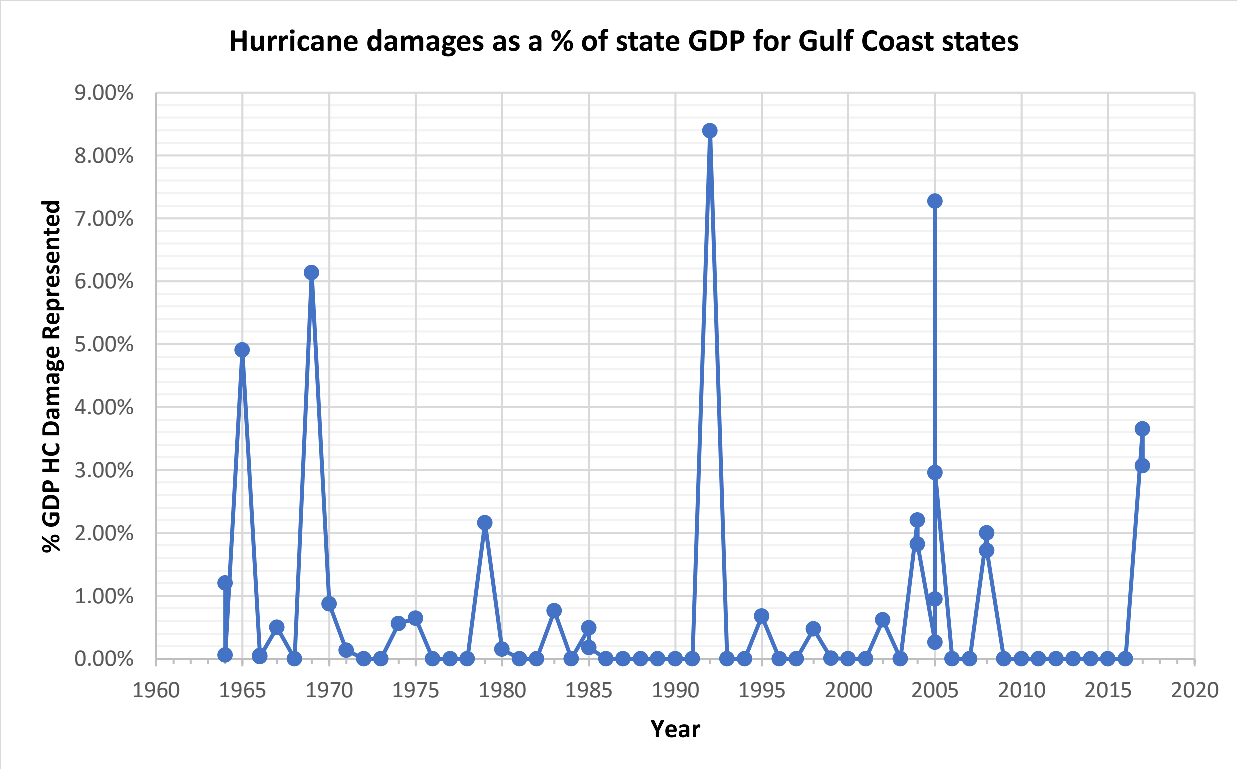

Figure 1.1 Hurricane damages as a percent of state GDP

Hurricane damages as a percent of state GDP for Gulf Coast states impacted by hurricane landfalls from 1964-2017.

The considerable average annual costs associated with hurricane landfalls to the Gulf Coast highlights the needed efforts to research and implement mitigation practices to limit the potential for such catastrophic losses. The increases in population and wealth to the region provides an explanation for the significant destruction over the time period, and the probable progression of losses for the future. Another primary concern of destructiveness along the Gulf Coast is related to the intensification of hurricanes in the Gulf of Mexico. The combination of these two elements will presumably influence the degree of economic losses in the future. Thus, mitigation will play a critical role in lessening the destructive potential of landfalling storms. While some research has been carried out on the relationship between hurricane activity and modes of climate variability, there has been little quantitative analysis of the association between modes of climate variability and destructiveness. In addition, no research has been found that has surveyed three different climate oscillations in association with intensification and destructiveness. The overall structure of the study takes the form of five chapters, including this introductory chapter. Chapter two deals with the intensification of hurricanes in the Gulf of Mexico associated with the three climate indices mentioned in the introduction. The third chapter is concerned with the destructiveness of hurricane landfalls to the Gulf Coast associated with each climate index. The fourth chapter presents an analysis of the findings, focusing on the significance of climate oscillations on the frequency, intensification, and destructiveness of landfalling hurricanes. Finally, the conclusion gives a brief summary of the findings, reiterates the significance of the study, and offers suggestions for future mitigation action.

CHAPTER II

ANALYSIS OF CLIMATE VARIABILITY EFFECT ON HURRICANE INTENSIFICATION RATES

Introduction

Over the past three decades, there has been an observable increase in the frequency and intensity of Atlantic hurricanes (Melillo et al., 2014). Fraza & Elsner (2013) found the highest mean intensification rates in the Gulf of Mexico and the Caribbean Sea. A number of studies have been published that suggest human-induced climate change is playing a role in the behavior of hurricanes (i.e. Henderson-Sellers et al., 1998, Emanuel, 2005, & Oouchi et al., 2006). For example, Henderson-Sellers et al. (1998), suggest the MPI of cyclones may undergo an increase of 10%-20% for a doubled CO_2. In spite of climate change, the cyclogenesis of hurricanes is influenced by natural climate oscillations as evident by historical records of alternating high and low hurricane activity that appear to align with changes in SSTs in the North Atlantic Ocean (Poore & Brock, 2011). Most research has focused on rapid intensification in regard to a specific storm, but little attention has been given to intensification over the tropical Atlantic basin (including the Caribbean Sea and the Gulf of Mexico). Additionally, extensive research has been carried out on the relationship between modes of climate variability and the frequency of hurricane landfalls to the U.S., but there has been little quantitative analysis of the relationship between modes of climate variability and the implication to hurricane intensification. This indicates a need to understand the variables that exist among these teleconnections and their significance on hurricane intensification.

The AMO is based upon the average SST anomalies in the North Atlantic (Zhang & Delworth, 2006). Additionally, the AMO has shown to be related to the Sahel rainy season and a faster thermohaline circulation, which contribute to major hurricane activity (Goldenberg et al., 2001). According to Goldenberg et al., (2001), the tropical North Atlantic has shown a warming trend of 0.3° C over the last century. During the positive phase, warmer SSTs reduce atmospheric stability promoting the formation of hurricanes (Goldenberg et al., 2001). Previous studies have shown that more major hurricanes impact the northern Gulf of Mexico when the AMO is positive (i.e. Goldenberg et al., 2001, Wang et al., 2008, and Poore & Brock, 2011). Goldenberg et al. (2001) found that the U.S. has sustained roughly five times as much damages from hurricane landfalls during the positive phase of the AMO compared to the negative phase.

During ENSO, lower sea level pressure and higher SSTs in the Atlantic basin were found to be associated with greater hurricane activity (Goldenberg & Shapiro, 1996). Additionally, Gray (1994) suggested that increases (decreases) in upper-level winds create unfavorable (favorable) conditions during El Nino (La Nina). During El Nino years, the intensity of Atlantic hurricanes was found to be weaker than during La Nina or Neutral years (Lupo & Johnston, 2000). Pielke and Landsea (1999) found there was a greater probability of more damaging hurricanes to make landfall along the U.S. coast during La Nina years. In a 73-year period study, they found that 77% of damaging hurricanes > $1 billion occurred during La Nina, 48% occurred during neural years, and 32% occurred during El Nino years. Although these findings demonstrate the significant effect La Nina has on billion-dollar events, Pielke and Landsea (1999) suggests that major hurricanes are of greater concern due to their substantial economic effects. The probability of at least one major hurricane making landfall during El Nino was about 23%, 58% for neutral conditions, and 63% during La Nina (Bove et al., 1998). ENSO is an important component of the climate system and plays a key role in the frequency of U.S. hurricane landfalls and economic damages that result.

The NAO results from differences in pressure between the subpolar low and the subtropical high which causes changes in winds and precipitation over the Atlantic. Elsner et al., (2000) found a correlation between the NAO and hurricane landfalls on decadal time scales. Specifically, the Gulf Coast endured more major hurricane strikes during negative NAO years. According to Elsner et al. (2000), the NAO serves as a cause for the shift in hurricane tracks. A weak subtropical high over the western North Atlantic keep hurricanes from recurving north, causing them to remain in lower latitudes where they tend to intensify before making landfall along the Gulf Coast (Elsner et al., 2000). In a 102-year period study it was found that the annual rate of hurricane landfalls was 0.38 per year during positive years and 0.86 during negative years (Elsner et al., 2003). Thus, during a negative NAO, the Gulf Coast was conducive to more than twice the landfalls than the positive phase. However, this was only significant from Texas to Alabama (Elsner et al., 2003).

One of the main purposes of this study is to assess the long-term relationship between hurricane intensification and natural climate variability, in a manner that is independent of climate change. Many environmental factors can contribute to hurricane intensification; however, this study examines solely the role of SST and intensity, which is measured by the maximum 1-minute average, sustained near-surface wind speed (Rappaport et al., 2010). By employing quantitative modes of enquiry, the study attempts to illuminate the significance of three modes of climate oscillations on hurricane intensification in the Gulf of Mexico.

Methods

This chapter will investigate the intensification of hurricanes in the North Atlantic and Gulf of Mexico. First, HURDAT data was used to create a histogram depicting the distribution of overall intensity change of hurricanes during the study period. Next, raster grids were created for the North Atlantic and Gulf of Mexico displaying the mean intensification, mean intensity, and mean SST over the study period. Additionally, raster grids were created for the Gulf of Mexico showing the number of intensifying storms throughout the basin during each phase of the three climate indices studied. Finally, statistical tests were run to calculate the relationship between variables including, intensity, intensification, and SST during each phase of the three climate indices studied.

The histogram, raster grids, and statistical tests were all done using R programming. Best Track Data came from the HURDAT dataset (Jarvinen et al., 1984). After each season, researchers at the National Hurricane Center (NHC) compile and analyze the data which contains 6-h data points (i.e. 00Z, 06Z, 12Z, 18Z) with the center of the hurricane (in latitude and longitude), as well as the intensity of the hurricane in 5 knot intervals. For the purposes of this study, HURDAT data was interpolated to one-hour intervals by using a Savitzky-Golay filter along with a cubic polynomial algorithm (Elsner & Jagger, 2013). This method allows for the 6-h data from the HURDAT dataset to be preserved. Further, it can allow for derivative calculations with a small amount of error, in order to find the hourly, intensity change of the hurricane.

Next, the years were filtered from 1900 to 2017, thereby collecting data on 657 storms. A histogram was created to examine the distribution of the overall intensity change, which revealed an increase of 0.012 m s^{-1} per hour (Figure 2.1).

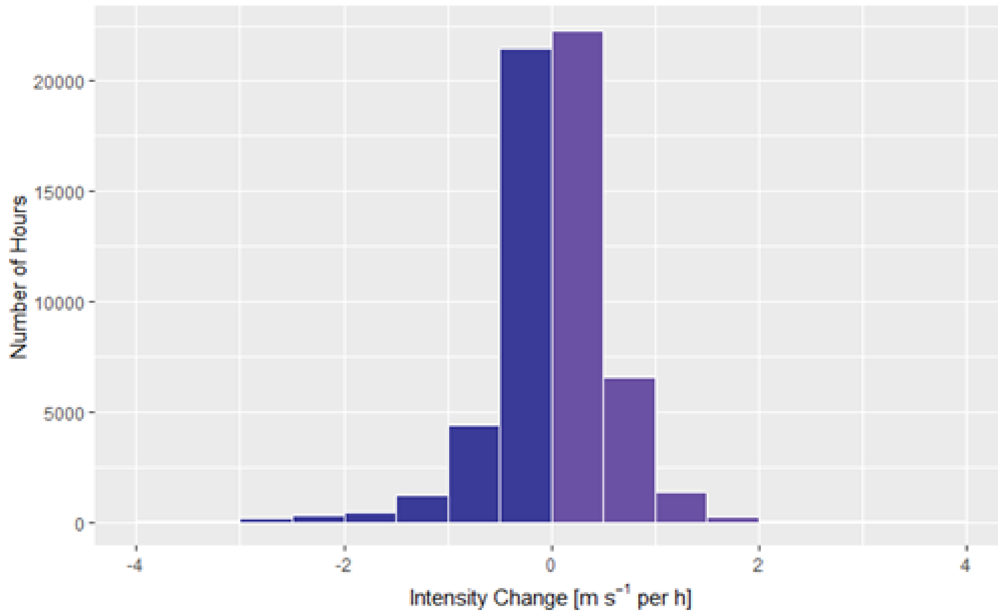

Figure 2.1 Overall intensity change histogram

Histogram showing the distribution of overall hourly intensity change over the period 1900-2017.

Hourly intensification values > 0 were filtered and all track points were put into a spatial points data frame, which allows the data to be put into raster form. From here, outlines for the Gulf of Mexico and the North Atlantic Basin were created to show borders in the frame being studied.

Using the "raster" package, 2° x 2° raster grid cells were created for the Gulf of Mexico, and 4° x 4° raster grid cells were created for the North Atlantic basin, allowing the variables of interest to be placed into the raster grids. For each variable plotted, all the values in each raster cell were taken together and then averaged. The raster cells for intensification, intensity and SST were then graphed on top of the outline maps for the Gulf of Mexico and North Atlantic basin.

Next, a correlation test and generalized linear model (GLM) were run for each phase of the three teleconnections of interest to determine the significance of the relationship between the three variables. The years were first filtered to positive and negative phases for each climate index using the Multivariate ENSO Index (MEI) (Wolter & Timlin, 2011) average values from August-September and September-October; the Hurrell North Atlantic Oscillation Index (station based) (Hurrell et al., 2018) for January, February, and March average anomalies; and the Kaplan Extended v2 SST anomaly dataset (Kaplan et al., 2019) for June-October average anomalies during the Atlantic Multidecadal Oscillation (AMO). The months used for the average anomaly data were evaluated based on being the strongest months for each climate index. The data was combined by the same latitude/longitude combinations into one data frame and the correlation was calculated. Next, the GLM was run and computed. Once the model was run, another line of code was run to see the results of the model, and then for the confidence intervals.

Finally, 2° x 2° raster grids were created for the Gulf of Mexico for each phase of the three teleconnections to display the number of hurricanes that intensified per cell over the study period. The primary focus was identifying the number of storms intensifying adjacent to the coastline. The attention to the coast provides a general judgement of the most vulnerable Gulf Coast regions. However, other clusters of cells that might have shown higher intensification counts were still considered in the analysis.

Mean intensification, intensity, and SST raster grids

Mean hourly intensification and mean intensity of all hurricanes to pass through each cell, as well as the mean SST of each cell were plotted in the North Atlantic basin. Mean intensification by cell is shown in Figure 2.2. The majority of the Gulf of Mexico, Caribbean Sea and Bahamas show mean intensification between 0.4-0.6 m s^{-1} per hour. Additionally, most of the cells in the tropics, east of the Lesser Antilles, display intensification between 0.4-0.6 m s^{-1}

per hour. Noteworthy pockets of higher intensification (0.6-0.8 m s^{-1} per hour) are seen off the coasts of Venezuela, Nicaragua, and Honduras. Broadly, cells north of 18° N, east of the Dominican Republic, display lower mean intensification values between 0.2-0.4 m s^{-1} per hour. This would be expected as water temperatures decrease further away from the equator. This grid reveals that hurricanes are intensifying by at least 0.4 m s^{-1} per hour throughout the Gulf of Mexico and Caribbean Sea.

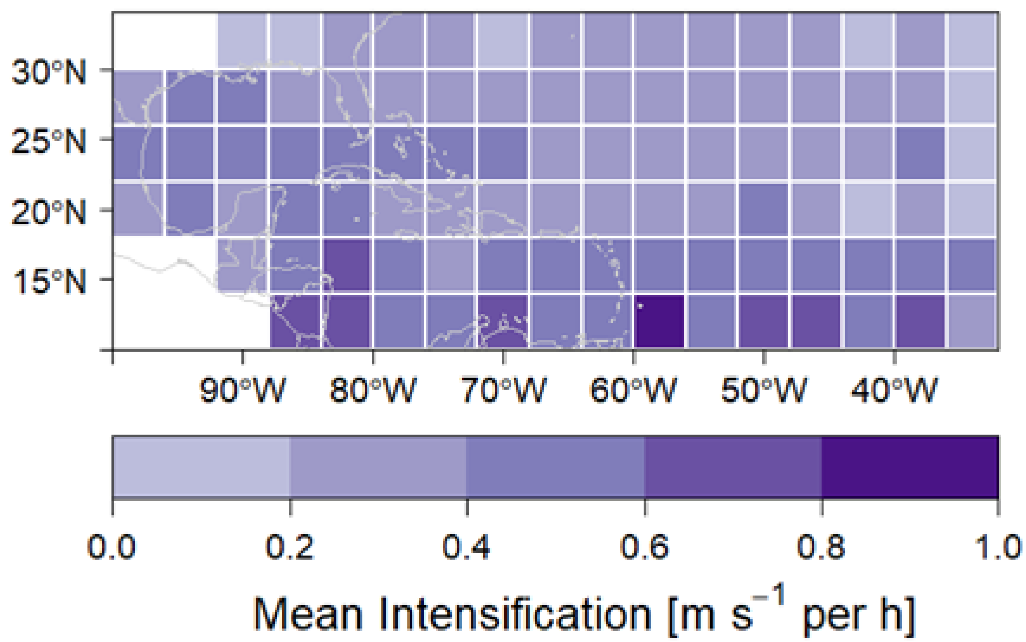

Figure 2.2 Mean intensification in North Atlantic

Raster grid of mean intensification by cell in the North Atlantic basin from 1900-2017.

A majority of the cells in the North Atlantic basin (Figure 2.3) show mean intensities between 40-45 m s^{-1}. A couple of pockets of higher intensity (50-55 m s^{-1}) can be seen near the central Bahamas and off the coast of Colombia and Venezuela. The central North Atlantic basin marks the lowest mean intensities of 35-40 m s^{-1}. This grid demonstrates that hurricanes are generally reaching highest intensities between 45-50 m s^{-1} in the Caribbean Sea, Yucatan Channel, and near the Bahamas.

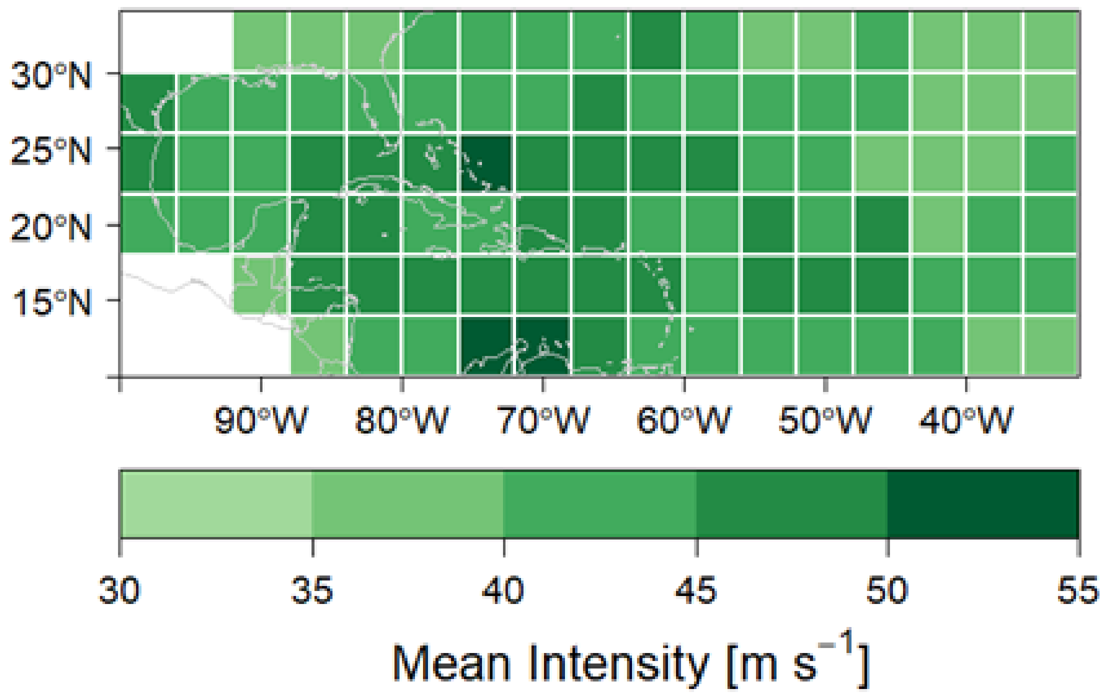

Figure 2.3 Mean intensity in the North Atlantic

Raster grid of mean intensity by cell in the North Atlantic basin from 1900-2017.

The North Atlantic basin (Figure 2.4), shows an increasing propagation in SST from the central part of the basin to the western edge of the basin (including the Caribbean Sea and the Gulf of Mexico). Significantly high SST of 28-29 °C are seen largely throughout the Gulf of Mexico and Caribbean Sea, extending just east of the Bahamas and Lesser Antilles. Pockets of highest SST (29-30 °C) are seen south of Cuba and near the Bay of Campeche. This grid highlights the distinguished SSTs seen in the western part of the basin, where populations are most susceptible to hurricane landfalls. As SSTs continue to rise as a result of global climate change, it is likely that hurricanes will increase in strength as they move over this region and advance toward the coast.

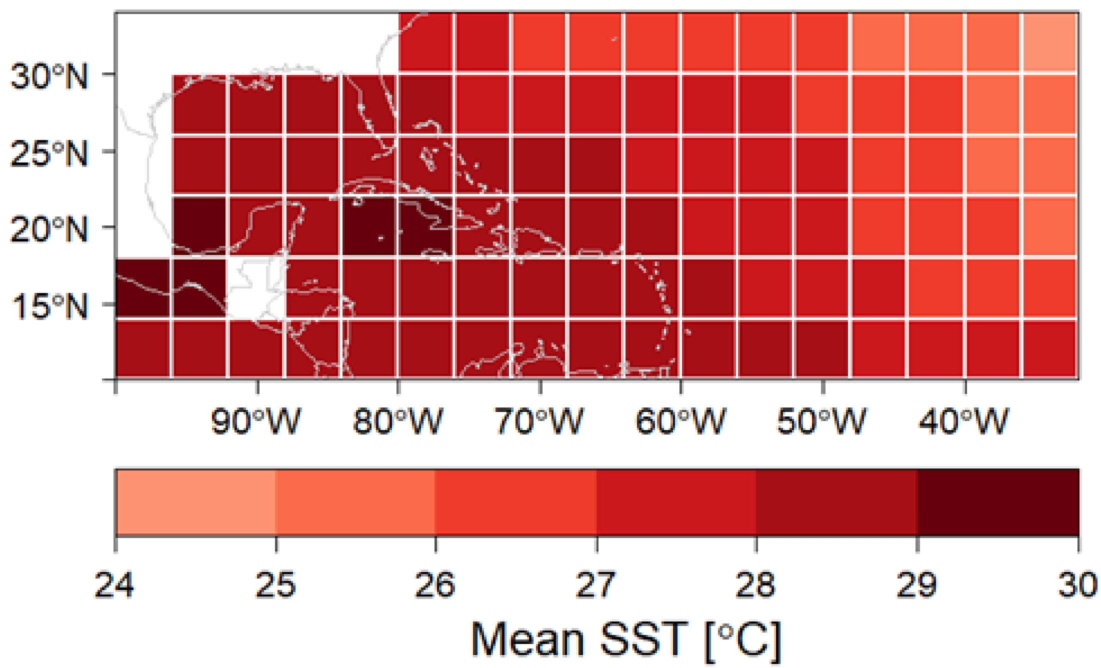

Figure 2.4 Mean SST in the North Atlantic

Raster grid of mean SST by cell in the North Atlantic basin from 1900-2017.

The North Atlantic basin shows significantly high SSTs (≥ 28 °C) in the Gulf of Mexico and the Caribbean Sea. The Gulf of Mexico and Caribbean Sea largely display mean intensities between 45-50 m s^{-1} and intensification between 0.4-0.6 m s^{-1} per hour. Given SSTs greater than or equal to 26.5 °C are an important factor in the cyclogenesis of hurricanes (Gray, 1968), it is apparent that warm SSTs are a critical factor in both the intensity and intensification of tropical cyclones.

Mean intensification, intensity and SST were next plotted in the Gulf of Mexico. A majority of the cells (Figure 2.5) show intensification between 0.4-0.6 m s^{-1} per hour, with scattered larger pockets reaching a maximum of 0.8 m s^{-1} per hour in the northwest Caribbean Sea, northwest region of the Gulf of Mexico, and near the center of the Gulf basin. Intensification is slightly lower (0.2-0.4 m s^{-1} per hour) along the coast from Brownsville, Texas to the Florida Panhandle. This observation is important for future work in monitoring mean intensification along the coast in order to improve the prediction of intensification before landfall.

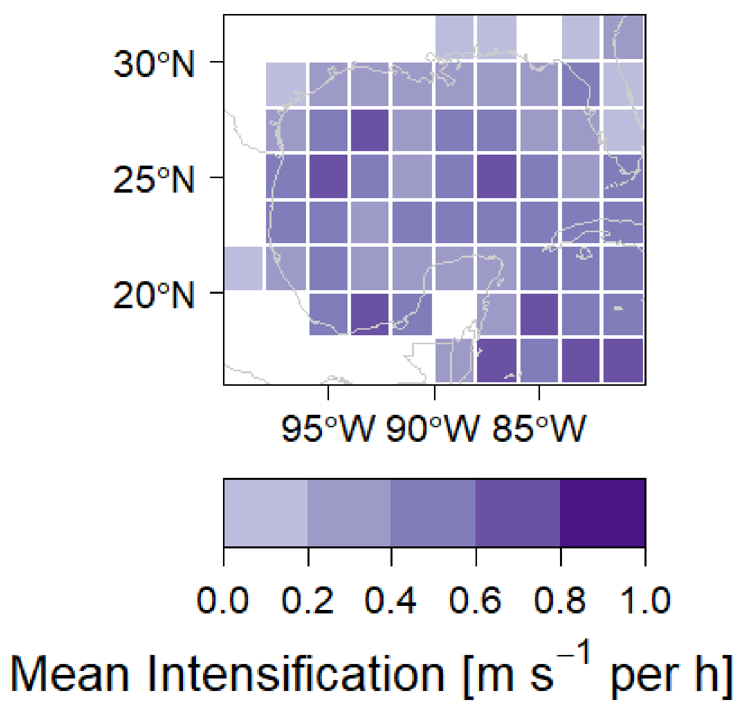

Figure 2.5 Mean intensification in the Gulf of Mexico

Raster grid of mean intensification by cell in the Gulf of Mexico from 1900-2017.

Mean intensity rates in the Gulf of Mexico (Figure 2.6) were largely between 45-50 m s^{-1} in the northwest of the Caribbean Sea and across the central region of the Gulf basin. The highest mean intensities (51-55 m s^{-1}) are scattered in cells off the coast of the Texas/Mexico border, in the center of the Gulf basin, and surrounding the Florida Keys. A majority of the cells throughout the western part of the basin show lower intensities between 40-45 m s^{-1}. Two pockets of lowest intensities seen in the basin (35-40 m s^{-1}) are adjacent to the Louisiana coast and in the Bay of Campeche, which could be due to hurricane weakening before making landfall. There is an observable trend in the intensity of 45-50 m s^{-1} moving north-northwest from the northwest region of the Caribbean to the central and northwest regions of the Gulf. The progression of these higher intensities toward the coastline should be monitored by climate scientists.

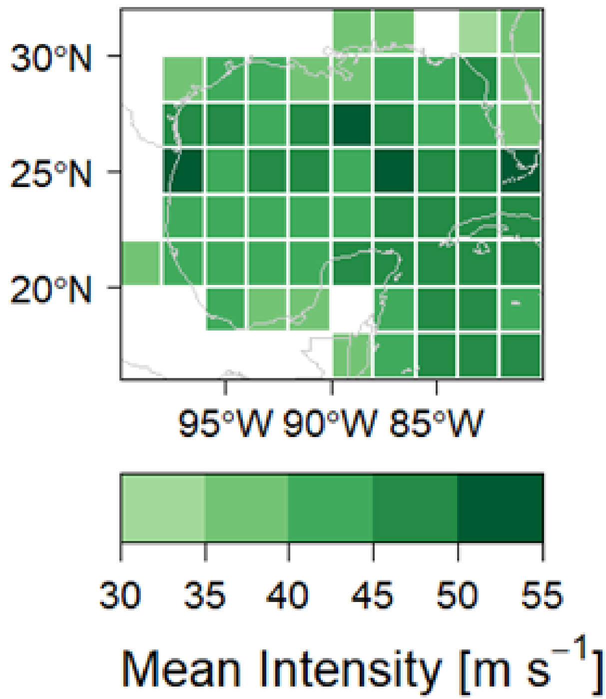

Figure 2.6 Mean intensity in the Gulf of Mexico

Raster grid of mean intensity by cell in the Gulf of Mexico from 1900-2017.

The mean SST (Figure 2.7) throughout the Gulf of Mexico is significantly high at least 28 °C. The northwest region of the Caribbean Sea and southwest region of the Gulf of Mexico have pockets of highest mean SST between 29-30 °C. The high SST seen surrounding Cuba is a prominent area for concern given this is a highly taken path of a hurricane into the Gulf, which can provide hurricanes with more energy as they advance toward the coast. The significantly high SST in the entire Gulf of Mexico, in part, explains the intensification ≥ 0.4 m s^{-1} per hour predominantly seen throughout the basin.

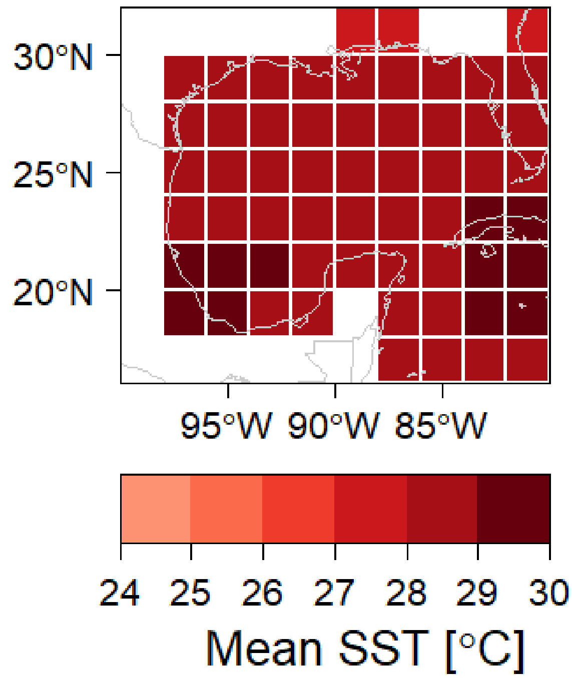

Figure 2.7 Mean SST in the Gulf of Mexico

Raster grid of mean SST by cell in the Gulf of Mexico from 1900-2017.

Overall, the entire Gulf of Mexico basin revealed SST ≥ 28 °C. Intensities ≥ 45 m s^{1} and intensification ≥ 0.4 m s^{-1} per hour were largely seen throughout the Caribbean moving northwest into the central Gulf of Mexico basin. From these grids, it can be inferred that generally where intensification is at least 0.4 m s^{-1} per hour is also where we can expect hurricane intensities of at least 45 m s^{-1}. While high SSTs provide a valid explanation for the intensification and intensity of hurricanes in the Gulf of Mexico and North Atlantic, as apparent from the raster grids, there are additional climatological factors that can influence these relationships on yearly, decadal and multidecadal time scales which will be investigated in the following section.

Climate variables

In this section, the relationship between three teleconnections and the intensification of hurricanes specific to the Gulf of Mexico were analyzed. Using R programming, a Pearson's product-moment correlation and generalized linear model (GLM) were run for each phase of the three climate indices. The results were interpreted using the p-value and sample estimates. The significance threshold was set at 0.05.

The El Nino Southern Oscillation (ENSO) data is represented by the Multivariate ENSO Index (MEI) (Wolter & Timlin, 2011). The values were averaged for the August/September and September/October months for each year and then separated into the positive phase (El Nino), negative phase (La Nina), or neutral phase. These months were used as they are significant to the Atlantic hurricane season given 95% of Saffir-Simpson category 3, 4, and 5 hurricane activity occur during August to October (ASO) (Pielke Jr., R. & Landsea, C., 1999). Values above 0.4 were classified as positive ENSO, values below -0.4 were classified as negative ENSO, and all others were classified as neutral years. A Pearson's product-moment correlation for the positive phase was calculated to test the relationship between the three variables of interest: intensification, intensity and SST. The data revealed there was a nonsignificant correlation between intensification and SST ($r = 0.215$, $p = 0.139$), and intensity and SST ($r = 0.188$, $p = 0.197$). There was an inverse relationship calculated from the correlation test between intensification and intensity ($r = -0.049$, $p = 0.739$) which demonstrates that Category 4 or 5 storms cannot intensify much further, whereas a lower category storm is more likely to intensify.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.541 m s^{-1} per hour, although the value is only significant at the 90% confidence interval. The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, it is expected that intensification would decrease by 0.006 m s^{-1} per hour ($p = 0.600$). The insignificant p-values of the GLM corroborate the findings from the correlation tests, emphasizing that the data does not show a relationship between the positive phase of ENSO and hurricane intensification in the Gulf of Mexico.

The same two tests were run for the negative phase of ENSO. The Pearson's product-moment correlation computed to assess the relationship between intensification and intensity (r = 0.419, $p < 0.001$), and intensification and SST (r = 0.299, $p = 0.025$) were both found to be significant above 95%. The correlation between intensity and SST was found to be statistically significant at the 90% (r = 0.25, $p = 0.064$). These calculations suggest that intensity has the greatest effect on intensification during the negative phase.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.243 m s^{-1} per hour ($p = 0.093$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.020 m s^{-1} per hour ($p = 0.047$). The findings from the GLM substantiate the calculations from the Pearson's product-moment correlation, indicating that intensity is playing the greatest role in intensification during the negative phase of this climate index.

Lastly, the Pearson's product-moment correlation was computed to assess the relationships between variables for the neutral phase of ENSO. The correlation tests for intensification and intensity (r = 0.293, $p = 0.027$), and intensification and SST (r = 0.320, $p = 0.015$) were both statistically significant above 95%. The correlation between intensity and SST was slightly lower (r = 0.227, $p = 0.089$), yet still significant above 90%. The results suggest that SST has the greatest effect on intensification during the neutral phase.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, while intensity is held constant, we would expect intensification to increase by 0.538 m s^{-1} per hour ($p = 0.004$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.018 m s^{-1} per hour ($p = 0.057$). This linear model supports the correlation tests and suggests that SST has the greatest role on intensification during the neutral phase of ENSO.

The second climate index analyzed was the North Atlantic Oscillation (NAO). The years were first filtered to the positive and negative phases using the Hurrell North Atlantic Oscillation Index (station based) (Hurrell et al., 2018) for January, February, and March average anomalies. These months were used as the NAO is strongest in March, followed by February and January (Portis et al., 2001). The Pearson's product-moment correlation was run first to observe the relationship between the three variables of interest for the positive phase. All three correlation tests were found to be significant above 95%. Based on the results, intensification was strongly related to intensity (r = 0.48, $p < 0.001$), and SST (r = 0.45, $p < 0.001$). While the relationship between intensity and SST was not as strong (r = 0.32, $p = 0.012$), it was still statistically significant at 95%.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.494 m s^{-1} per hour ($p = 0.004$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.038 m s^{-1} ($p = 0.002$). These findings support the correlation tests and validate the observed effect intensity and SST have on hurricane intensification during the positive phase.

The same two tests were run for negative phase of the NAO. The Pearson's product-moment correlation for all three variables were found, again, to be significant above 95%. The relationships between intensification and intensity (r = 0.392, $p = 0.003$), and intensification and SST (r = 0.391, $p = 0.003$), were equally significant, though not as strong as seen during the positive phase. The relationship between intensity and SST was not as strong (r = 0.306, $p = 0.022$), however still significant at the 95% confidence level.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.679 m s^{-1} per hour ($p < 0.001$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.028 m s^{-1} per hour ($p = 0.015$). The findings suggest that intensity and SST have a statistically significant relationship with hurricane intensification during the negative phase. Interestingly, no significant differences were found between all three variables for the positive and negative phases of the NAO.

The data from the correlation tests and the linear model indicate intensity and SST have a statistically significant positive relationship with intensification during both phases. Although it is expected the significance would be higher during the negative phase, other variables may be having a stronger effect that are not included in the analysis. For example, reduced wind shear could be having a greater effect on intensification during the negative phase which would account for the weaker relationship between the included variables, whereas in the positive phase it is not as much of a factor. It is possible that since the NAO is primarily an atmospheric mode it is marginally affected by SST (Barnston, A. & Livezey, R., 1987). Due to the lack of statistical differences in the findings between the negative and positive phases, the data was reduced to only the twenty most positive and most negative NAO years.

The top 20 years for the positive phase of the NAO were gathered and the Pearson product-moment correlation tests were run for all three variables. The results were considerably different than the initial observations. The correlation tests revealed that all three relationships were insignificant at 95%. More specifically, the data revealed there was a nonsignificant relationship between intensification and SST (r = 0.199, p = 0.169), and intensity and SST (r = 0.242, p = 0.094). The correlation between intensification and intensity revealed an inverse relationship between the variables (r = -0.033, p = 0.821). The insignificant p-values indicate that there is no observable relationship between strong, positive NAO years and hurricane intensification.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.452 m s^{-1} per hour, (p = 0.115). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification would decrease by 0.008 m s^{-1} per hour (p = 0.451). The data revealed by the linear model supports the calculations reported by the correlation tests, prompting the conclusion that observations between variables during a strong, positive NAO are statistically insignificant and therefore, have no detectable effect on intensification.

Next, the top 20 years for the negative phase were gathered and the Pearson product-moment correlation tests were run for all three variables. The results indicated that the relationships between intensification and SST (r = 0.166, p = 0.249), and intensity and SST (r = 0.056, p = 0.698) were insignificant at 95%. However, there was a statistically significant relationship between intensification and intensity (r = 0.502, $p < 0.001$). This test suggests that intensity has a considerable effect on intensification during a strong, negative NAO.

The results of the GLM for the SST coefficient shows that for every 1 °C increase in SST, intensification is expected to increase by 0.462 m s^{-1} per hour ($p = 0.046$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.029 m s^{-1} ($p < 0.001$). While the observations between variables from the linear model are both shown to be statistically significant, it can be argued that intensity shows the greatest effect on intensification during a strong, negative NAO. The results of the statistical tests for the top positive and negative years of the climate index support the initial prediction that the negative phase would have a greater effect on intensification in the Gulf of Mexico.

The final climate index analyzed was the Atlantic Multidecadal Oscillation (AMO). The years were filtered to the negative and positive phases using the Kaplan Extended v2 SST anomaly dataset (Kaplan et al., 2019) for June-October average anomalies. The AMO was in the negative phases from 1900-1925 and 1970-1994, and in the positive phases from 1926-1969 and from 1995 to the present. A Pearson's product-moment correlation test was calculated for all three variables. The results revealed that all three relationships were significant above 95%. Based on the results, the relationship between intensification and intensity was the strongest (r = 0.51, $p < 0.001$). However, the relationship between intensification and SST was also highly significant (r = 0.49, $p < 0.001$). While the relationship between intensity and SST was not as strong (r = 0.29, $p = 0.023$), it was still statistically significant above 95%. These findings signify the considerable effect the positive phase of the AMO has on hurricane intensification.

The results of the GLM for the SST coefficient shows that for every 1°C increase in SST, intensification is expected to increase by 0.666 m s^{-1} per hour ($p < 0.001$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.038 m s^{-1} per hour ($p < 0.001$). This model corroborates the results from the correlation tests and illustrates a highly significant relationship between variables, indicating that SST and intensity play a role in hurricane intensification in the Gulf of Mexico during the positive phase of the AMO.

Finally, a Pearson's product-moment correlation was calculated for all three variables for the negative phase of the AMO. The data revealed that the relationship between intensification and intensity (r = 0.254, $p = 0.062$) was insignificant at the desired confidence level. SST was found to have the greatest effect on intensification during the negative phase (r = 0.291, $p = 0.033$). The relationship between intensity and SST was found to be significant at the 95% (r = 0.270, $p = 0.048$). While the correlations between intensification and SST, and intensity and SST were both significant at at least 95%, these findings suggest that the negative phase of the AMO does not have as strong of a relationship with hurricane intensification when compared to the positive phase.

The results of the GLM for the SST coefficient shows that for every 1°C increase in SST, intensification is expected to increase by 0.311 m s^{-1} per hour ($p = 0.038$). The results for the intensity coefficient show that for every 1 m s^{-1} increase in intensity, intensification is expected to increase by 0.013 m s^{-1} per hour ($p = 0.17$). Again, SST shows to have the greatest effect on intensification during the negative phase, supporting the results of the correlation tests. However, these results maintain that the variables observed during the positive phase of the AMO have a more pronounced effect on intensification in the Gulf of Mexico.

The Pearson's product-moment correlation tests and GLM provided a general understanding of relationships between intensification, intensity and SST in the Gulf of Mexico. The data revealed for each phase of the three climate indices supported the expected findings based on long-term climatological patterns. Furthermore, the data established a clear indication of the likelihood for hurricane intensification during certain phases of each teleconnection. Each phase of the three teleconnections studied showed marked differences in the statistical relationship between intensification, intensity and SST. These findings can better assist policy makers and other stakeholders in preparing for and mitigating the effects of hurricanes along the coast of the Gulf of Mexico based on prior climate patterns.

Intensification counts related to climate variables

Data for each climate index was filtered to the respective phases and raster grades were created to display the number of intensifying hurricanes in the Gulf of Mexico. Higher numbers of intensifying storms near the coast will allow stakeholders to gauge their susceptibility to increased destructiveness. The number of intensifying hurricanes throughout the Gulf of Mexico basin for the positive phase of ENSO (Figure 2.8) is generally less than 5. One cell southeast of Texas shows between 5-10 hurricanes intensifying and should be noted by climate scientists, but overall, the positive phase of ENSO does not show any reason for drastic concerns of intensifying hurricanes.

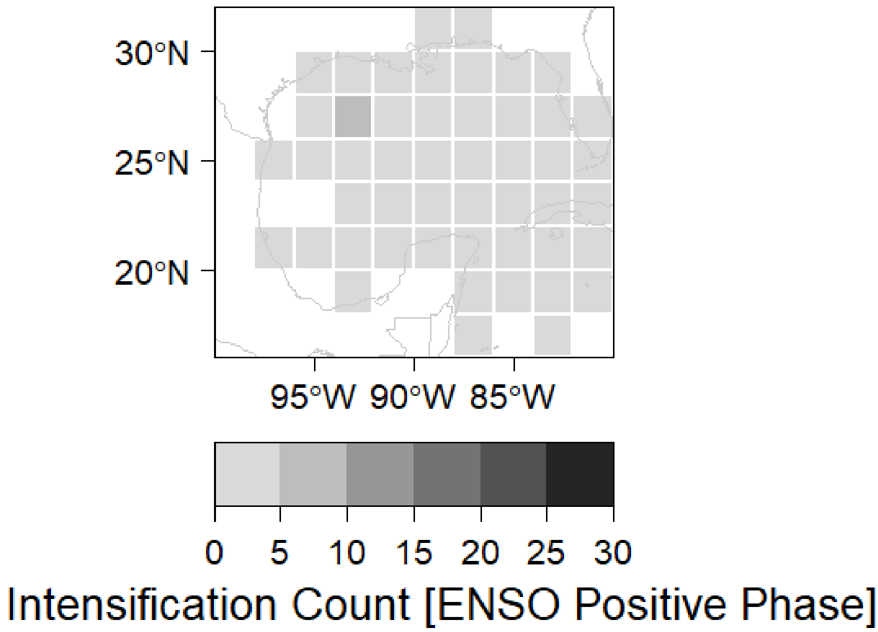

Figure 2.8 Intensification Counts [ENSO Positive Phase]

Raster grid of intensification counts by cell during the positive years of ENSO.

The negative phase of ENSO (Figure 2.9) shows significantly more intensification counts throughout the basin. The highest number of intensifying hurricanes (10-20) is seen in the northwest of the Caribbean Sea and through the Yucatan Channel to the center of the Gulf of Mexico basin. Another pocket of 10-15 storms intensifying is seen off the east coast of Mexico. Along the coast from central Texas to central Florida, the number of intensifying hurricanes is less than 5. However, moving further south to the Florida Keys, the number of intensifying hurricanes increases to between 5-10. This cell is also where the highest mean intensities are seen, as evident by the mean intensity raster grid, and the abundance of landfalls in our study. The Florida Keys have withstood the calamities brought on by Hurricanes: Irma (Category 4), Wilma (Category 3), Betsy (Category 3), Donna (Category 4), October 1948 (Category 3), September 1948 (Category 3), 'Labor Day' 1935 (Category 4), 1919 (Category 4), ‘Cuba’ 1910 (Category 4), 1909 (Category 3), and 1906 (Category3) (Lovin, n.d.). Additionally, the number of hurricanes intensifying off the coast of central Texas and south of Louisiana is between 5-10. These cells are also where high intensification and intensity values are observed, drawing attention to the low-lying Galveston/Houston & New Orleans regions. The extensive flooding and damage brought on by Hurricanes Harvey (2017) and Katrina (2005) to these regions is likely to happen again as the number of intensifying storms increase. Overall, the negative phase of ENSO clearly shows higher counts of intensifying hurricanes than the positive phase. While most of the higher intensification counts are seen in the southern half of the basin, these areas are still of significance as these intensifying storms propagate through these regions of the Gulf and toward the coastline. Moreover, as SST continue to rise due to climate change, intensification counts could rise near the coast, prompting urgent attention from stakeholders as a means for awareness during this phase of ENSO.

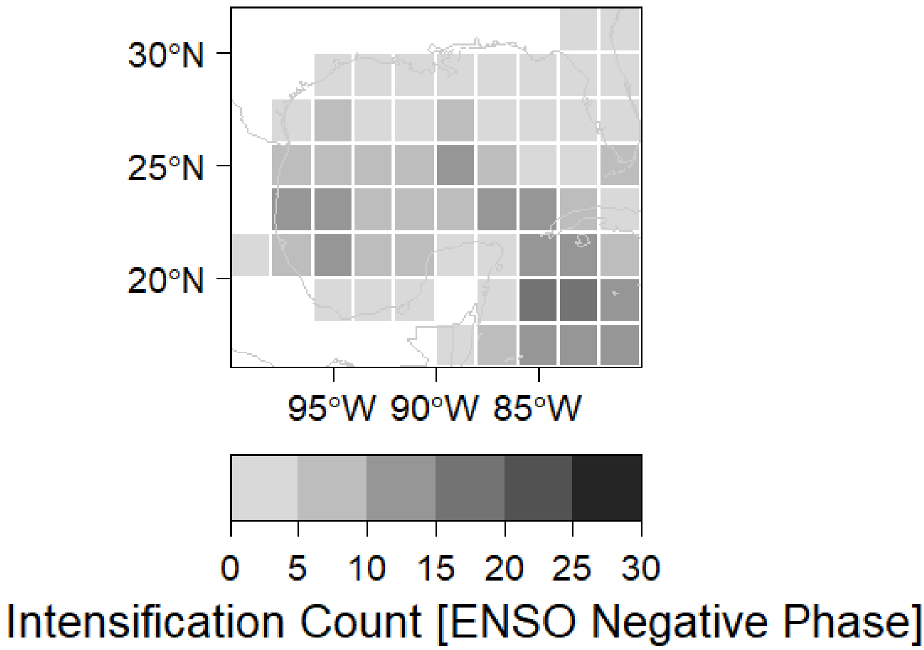

Figure 2.9 Intensification Counts [ENSO Negative Phase]

Raster grid of intensification counts by cell during the negative years of ENSO.

The number of hurricanes intensifying during the neutral phase of ENSO (Figure 2.10) is less than 5 throughout the majority of the Gulf of Mexico. A few cells near Galveston, Texas, and between Vermilion Bay and Barataria Bay, Louisiana show slightly higher numbers of intensifying hurricanes (5-10). Both locations have faced historic hurricanes, including Hurricane Harvey (Category 4) which wreaked havoc on the Galveston/Houston area of Texas in 2017, and Hurricane Katrina (Category 5), which was one of the most devastating natural disasters in U.S. history (Medlin et al., 2016) as it made landfall near New Orleans, Louisiana in 2005. Scattered cells off the coast of western Florida and south of Cuba show higher numbers of intensifying hurricanes between 10-15. However, the number of hurricanes intensifying throughout the Caribbean is predominantly between 5-10.

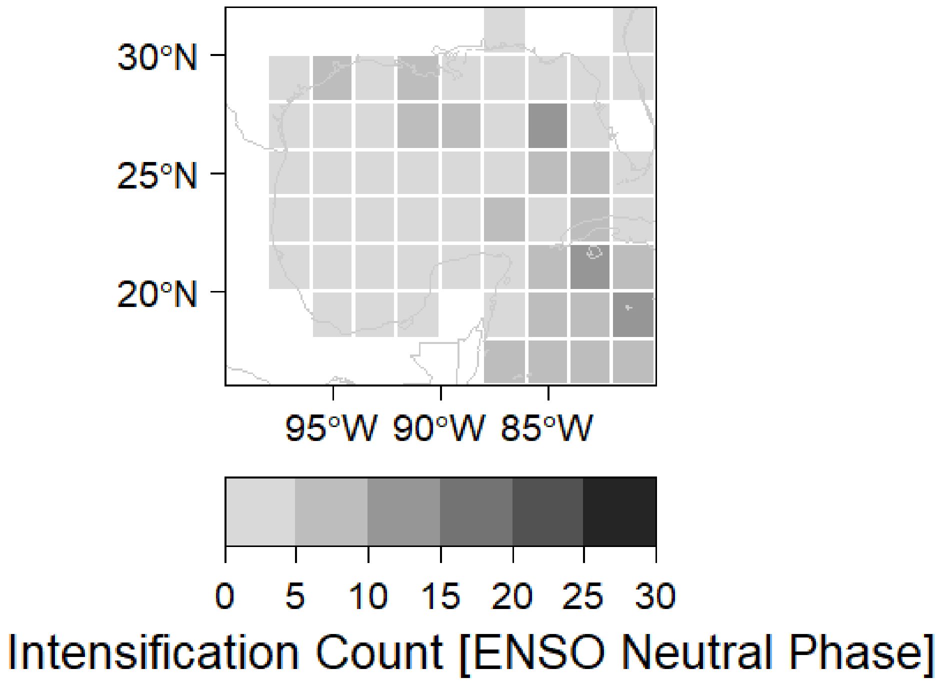

Figure 2.10 Intensification Counts [ENSO Neutral Phase]

Raster grid of intensification counts by cell during the neutral years of ENSO.

While the negative phase of ENSO clearly shows higher counts of intensification throughout the basin, the neutral phase should still be of high regard to stakeholders along the coasts near Galveston, Texas and southern Louisiana, as these regions are low-lying and have already encountered between 5-10 hurricanes that intensified in proximity to the shoreline. Additionally, stakeholders on the Peninsula of western Florida and along the Panhandle should be aware of the influence of the Loop Current, which brings warm water from the Caribbean into the Gulf. As seen on the SST grid (Figure 2.7), the highest sea surface temperatures are in the Caribbean, south of Cuba. The Loop Current brings this extremely warm water into the Gulf passing by the Yucatan, and loops clockwise in the basin before moving through the Florida Strait. This process possibly contributes to the high counts of intensifying storms seen slightly further off the Peninsula of western Florida.

The positive phase of the NAO (Figure 2.11) shows an apparent significant trend in the number of hurricanes intensifying (ranging between 10-20) in the Caribbean Sea and moving northwest through the Yucatan Channel into the central Gulf of Mexico basin. The more predominant areas for concern are near Galveston, Texas and the Texas/Louisiana border where 5-10 hurricanes are intensifying directly adjacent to the coast. Outflow from the Mississippi River lowers the salinity and density of the water in this region. Thus, it takes a greater amount of energy for the mixing of ocean water here, allowing the water to remain static and heat up (Ffield, 2007). This freshwater intrusion could be aiding in the intensification counts seen south of the Louisiana coast. Continuing along the coastline from the Florida Panhandle to the Peninsula, the number of intensifying hurricanes remains less than 5. However, southern Florida and the Keys show 5-10 hurricanes intensifying, which is also where the highest mean intensities are seen. As mentioned earlier, the Loop Current carrying warm Caribbean water through the Florida Strait could be influencing the intensification counts here.

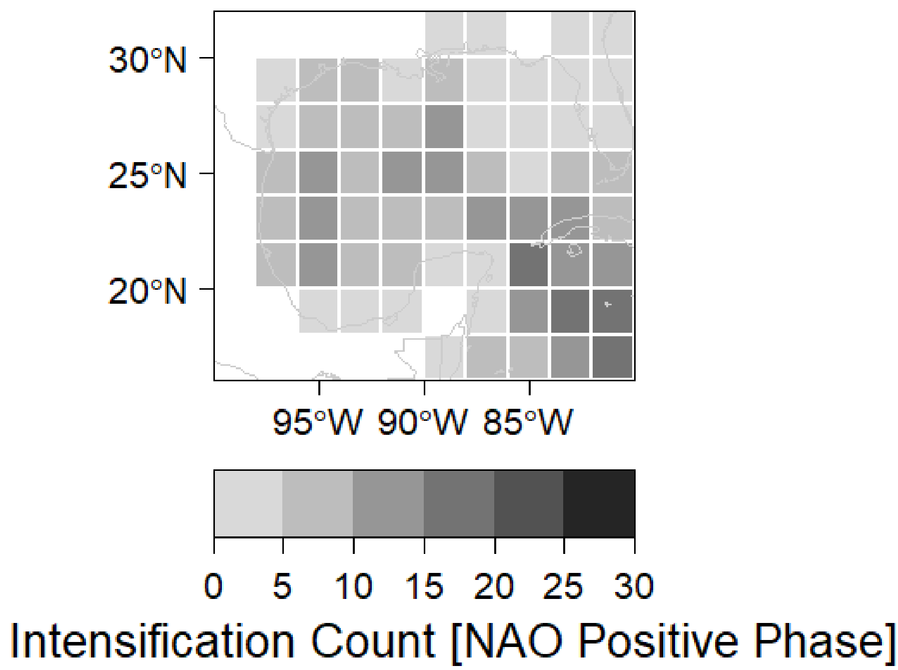

Figure 2.11 Intensification Counts [NAO Positive Phase]

Raster grid of intensification counts by cell during the positive years of the NAO.

The negative phase of the NAO (Figure 2.12) does not show as many intensifying storms throughout the basin. The northern half of the basin and predominantly throughout the Caribbean, the number of intensifying hurricanes is between 5-15. A few cells adjacent to the coastline from Port Lavaca, Texas to Morgan City, Louisiana, and near Pensacola, Florida shows 5-10 hurricanes intensifying. Though not directly adjacent to the coast, there are a few other cells that should be recognized by climate scientists. The number of hurricanes intensifying further off the coast of Louisiana and the Florida Peninsula is between 10-15, making these coastlines still reasonably vulnerable to intensified hurricane landfalls. Initial observations did not reflect the assumption that the negative phase of the NAO would have more of a distinguishable effect on the number of intensifying hurricanes. Thus, raster grids were created for only the top 20 positive and negative years to identify the effect of a strong NAO on the number of intensifying hurricanes.

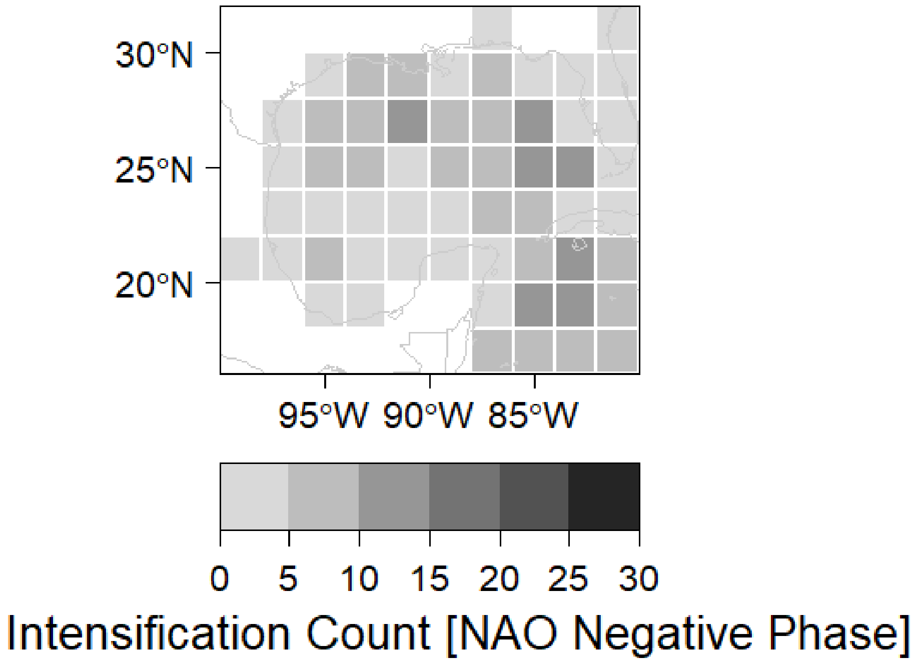

Figure 2.12 Intensification Counts [NAO Negative Phase]

Raster grid of intensification counts by cell during the negative years of the NAO.

The top 20 positive years for the NAO (Figure 2.13) widely shows less than 5 hurricanes intensifying throughout the basin. There is a pocket in the northwest region of the Caribbean Sea where the number of intensifying hurricanes is slightly higher (5-10). Many cells off the coast of the Florida Panhandle and Peninsula are blank, indicating zero intensifying hurricanes. This grid supports the initial expectation that the positive phase does not have a significant effect on hurricane intensification.

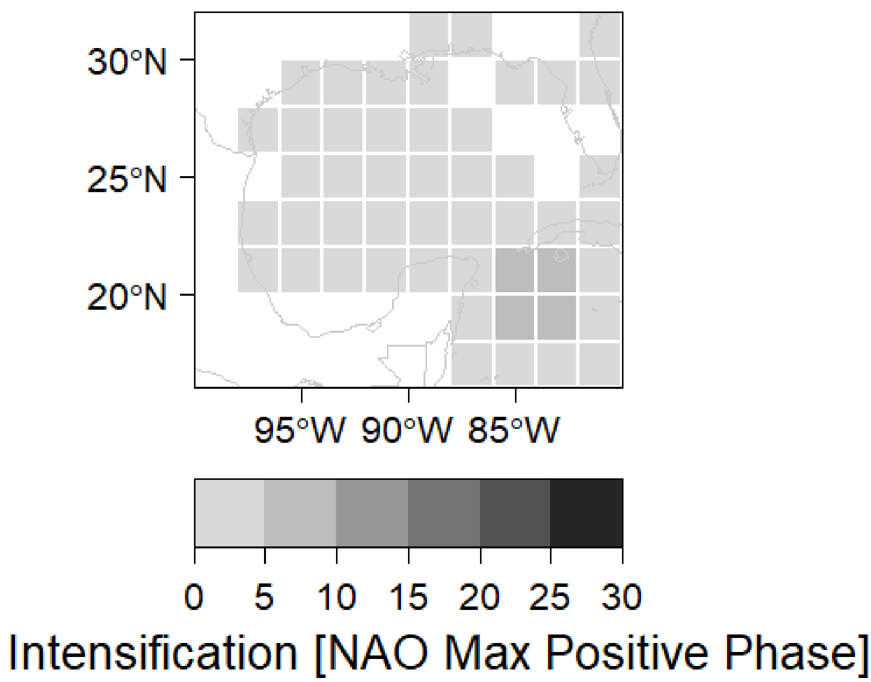

Figure 2.13 Intensification Counts [NAO Max Positive Phase]

Raster grid of intensification counts by cell during the top positive years of the NAO.

The top 20 negative years (Figure 2.14) is relatively similar to the top 20 positive years grid (Figure 2.13), making it difficult, again, to definitively rule that one phase has a more noticeable effect on hurricane intensification. However, upon closer observation, the top negative years grid has fewer cells with zero intensification counts, indicating almost every cell throughout the basin has encountered between 1-5 intensified hurricanes. Also, the higher number of intensifying storms (5-10) are seen much closer to the U.S. Gulf Coast, offering a more persuasive argument that a strong, negative NAO has a greater impact on intensifying hurricanes near the coast than a weak, positive NAO.

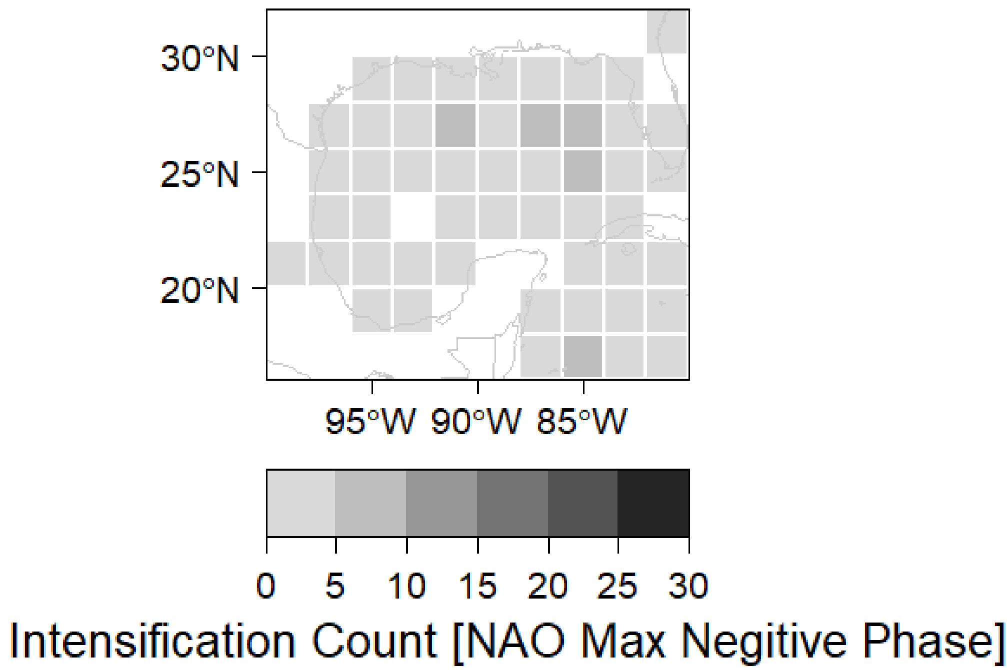

Figure 2.14 Intensification counts [NAO Max Negative Phase]

Raster grid of intensification counts by cell during the top negative years of the NAO.

The positive phase of the AMO (Figure 2.15) largely shows between 5-10 hurricanes intensifying throughout the Gulf of Mexico, with some scattered cells of higher counts (ranging between 10-20). The Caribbean Sea has the highest numbers of intensifying hurricanes (ranging from 10-25). However, a more predominant area for concern is along the coastline from the Louisiana/Mississippi border to Port Lavaca, Texas, where the number of intensifying hurricanes is between 5-10 per cell. Another area that stands out for concern is along the coast from central Florida to the Keys. Here, between 5-15 hurricanes are intensifying. This is also where the highest mean intensities of 45-55 m s^{-1} are seen, highlighting the needed awareness from stakeholders in preparing for, and mitigating the effects of intensifying hurricanes that make landfall in these coastal counties.

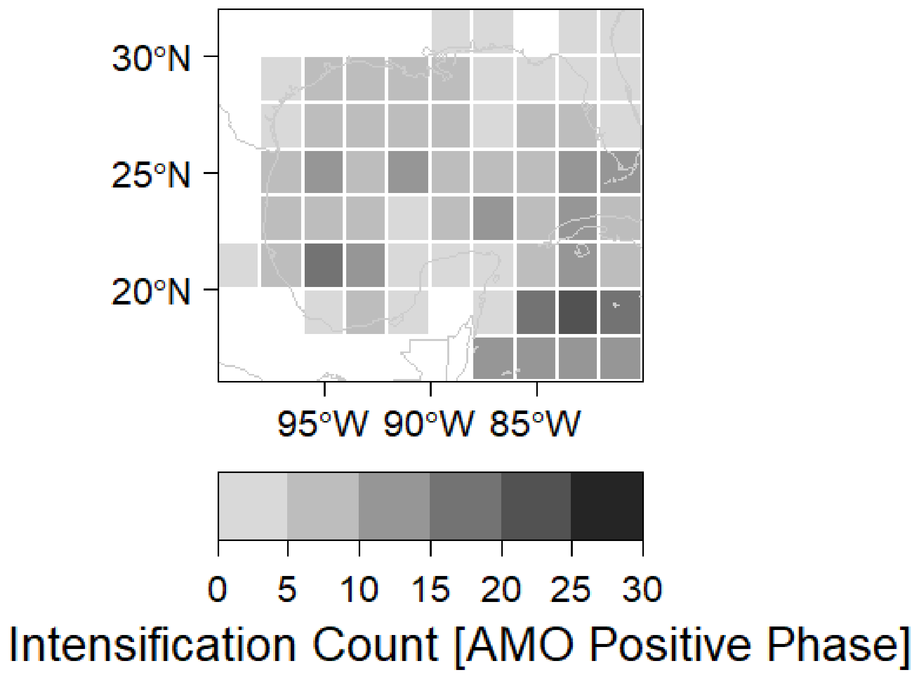

Figure 2.15 Intensification Counts [AMO Positive Phase]

Raster grid of intensification counts by cell during the positive years of the AMO.

The negative phase of the AMO (Figure 2.16) does not show as many higher counts of intensifying hurricanes throughout the basin as the positive phase does. The majority of the basin generally shows between 5-10 hurricanes intensifying, with one cell south of Louisiana displaying 10-15. In the Caribbean Sea, south and west of Cuba, the number of intensifying hurricanes is highest (ranging between 10-20). Along the coastline, there is not much of a concern from Brownsville, Texas to the Florida Keys. Two cells that might be of greater concern, however, would be the coast near the Texas/Louisiana border, and the coast near Pensacola, Florida where the number of intensifying hurricanes is between 5-10. Overall, the negative phase of the AMO does not show as many intensifications counts along the Gulf Coast.

Therefore, stakeholders should be more cognizant of intensifying storms during the positive phase.

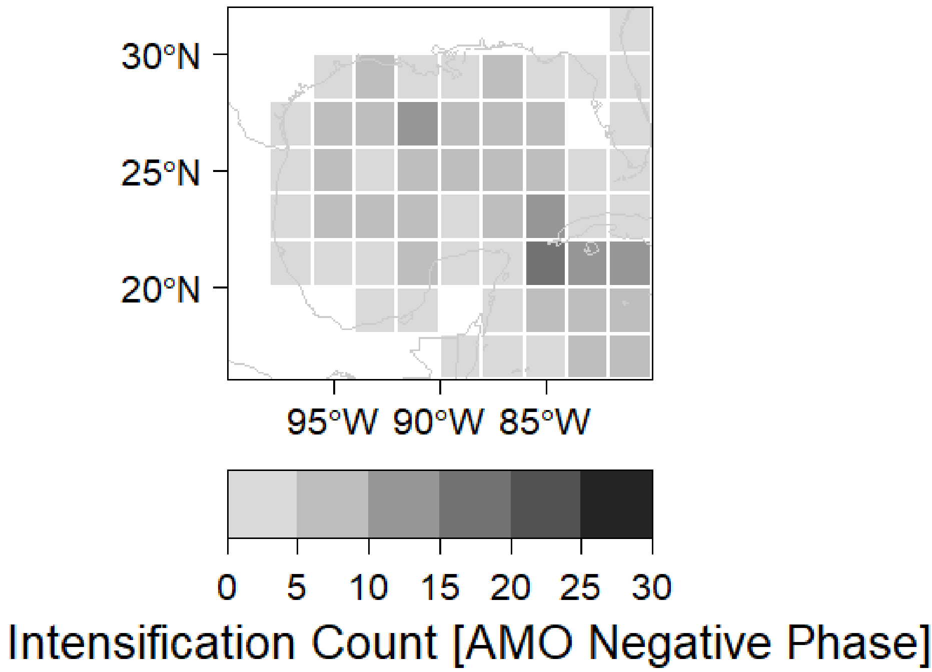

Figure 2.16 Intensification Counts [AMO Negative Phase]

Raster grid of intensification counts by cell during the negative years of the AMO.

Discussion

The findings presented in this chapter illustrate the locations of the highest mean intensification, intensity and SST values throughout the Gulf of Mexico. Additionally, the statistical tests revealed the relationship between the variables of interest during the various phases of each climate index. Finally, hurricane intensification counts were laid out on raster grids highlighting the Gulf Coast's exposure to intensifying hurricanes.

Generally, the Gulf of Mexico showed mean intensification of 0.4 m s^{-1} per hour or greater over the study period. The highest mean intensities of 51-55 m s^{-1} were seen near Brownsville, Texas, south of Louisiana in the central region of the basin, and along the southern coast of the Florida Peninsula and surrounding the Keys. However, most of the western part of the basin and the Caribbean Sea displayed mean intensities between 45-50 m s^{-1}. The entire basin displayed mean SST ≥ 28° C, with the highest temperatures seen in the Florida Strait and south of Cuba in the Caribbean Sea, and off the eastern coast of Mexico. Overall, the high SSTs are likely a cause for the intensification and high intensities seen throughout the basin. More specifically, the Loop Current, which brings this warm ocean water from the Caribbean into the Gulf of Mexico, and then passes through the Florida Strait, could be attributing to the high mean intensities and number of intensifying storms seen throughout the basin. Hurricanes that pass over this warm current can gain energy, allowing them to intensify and become stronger as they propagate toward the coastline.

The statistical tests and intensification count raster grids for each climate index revealed that the positive phase of the AMO had the greatest effect on hurricane intensification. Additionally, the raster grid for the positive phase of the AMO showed the highest numbers of intensifying storms along the Gulf of Mexico coastline from Brownsville, Texas to the Florida Keys. This climate index should be of topmost regard to Gulf Coast residents, business owners, and policy holders in preparing for and mitigating the effects of expected intensified hurricanes that could make landfall during this climate oscillation.

The statistical tests for the positive and negative phases of the NAO were not shown to be exceptionally different, although the relationships between variables for the positive phase were slightly more significant than the negative phase. Additionally, the positive phase showed much higher intensification counts throughout the basin. These findings did not align with the expectation that the negative phase would have a more discernible effect on hurricane intensification. The discrepancy pertaining to the statistical relationships between variables, and intensification counts during the positive and negative phases of the NAO may be due to variables not included in the analysis, such as wind shear. However, when taking into consideration only the extreme positive and negative years, the findings were more lucid. The statistical tests revealed a significant relationship to intensity, and there were greater intensification counts nearer to the coastline during the negative phase. Thus, a strong, negative NAO was shown to have a greater effect on intensification than the positive phase for the extreme NAO years. Still, a more thorough investigation of the NAO's influence on hurricane intensification in the Gulf of Mexico is needed to draw a conclusive assertion on the dominant phase of the climate index.

Finally, the negative phase of ENSO was also found to have a substantial effect on hurricane intensification. The statistical tests revealed that intensity had the greatest influence on intensification. SST also had an observable relationship with hurricane intensification during this phase, however, not as marked. The neutral phase was also shown to have a statistically significant effect on intensification, but the relationships were opposite that of the negative phase, meaning that SST had a greater influence on intensification than intensity. The intensification counts were undoubtedly higher during the negative phase than the neutral phase. However, most of these greater intensification counts were seen in the southern half of the basin, not directly along the coastline. The only area where intensification counts were ≥ 5 and adjacent to the coastline, was along the southern part of the Florida Peninsula, and the Keys. It should be noted, though, the trend of higher intensification counts is seemingly moving northwest, from the Caribbean Sea to the center of the basin. With the influence of climate change on SST, it could be possible to see these higher numbers of intensifying hurricanes continue to move closer to the Louisiana coastline. Despite the neutral phase displaying lower counts throughout the basin, there were two areas directly adjacent to the coastline where intensification counts were ≥ 5. These areas include Galveston, Texas and Morgan City, Louisiana. Both regions are low-lying and have experienced devastating hurricane landfalls in the past. It is likely these regions could see intensified hurricane landfalls again in the future.

The statistical analysis presented in this chapter substantiates the role of natural climate oscillations on the intensification of hurricanes in the Gulf of Mexico. Overall, the positive phase of the AMO, negative phase of ENSO, and the strongest twenty, negative NAO years, exhibited the most significant influence on hurricane intensification in the Gulf of Mexico. These findings support the claim by Bell and Chelliah (2005) that tropical multidecadal modes are shown to link fluctuations in Atlantic hurricane activity which result from oceanic and atmospheric conditions. Specifically, the finding by Pielke and Landsea (1999) that the probability of U.S. landfalling hurricanes increases during La Nina years was shown to be accurate over this study period. Additionally, the positive phase of the AMO showed to be of significance to intensification of hurricanes in the Gulf of Mexico supporting Goldenberg et al. (2001), Wang et al. (2008), and Poore & Brock (2011) who found that there are greater occurrences of major hurricanes in the Gulf of Mexico when the AMO is positive. The findings in this chapter pertaining to the NAO do not support previous findings by Elsner et al. (2000) that the negative phase is conducive to more major hurricanes in the Gulf of Mexico. The significance of a negative NAO phase was more conspicuous when accounting for only extreme NAO values. The oceanic and atmospheric processes that occur during each climate index are explained in the next chapter. Accordingly, stakeholders should be cognizant of how these climate oscillations influence the strength of tropical cyclones that can make landfall along vulnerable coastal counties, causing catastrophic losses.

CHAPTER III

ANALYSIS OF DESTRUCTIVENESS ASSOCIATED WITH CLIMATE VARIABILITY

Introduction

In the coming decades, the influence of anthropogenic climate change, in addition to population and wealth growth along the Gulf Coast, will place increased stress on the catastrophic losses that result from landfalling hurricanes. The calamitous effects will place great strain on local businesses, agriculture, and tourism sectors along the Gulf of Mexico. According to Deryugina (2017), hurricanes reduce income growth for at least 20 years in developed countries. Thus, an understanding of climate variability is critical in determining preventative measures in a regime where the threat of landfalling hurricanes is much greater (Goldenberg, 2018). Additionally, measuring the fiscal costs of hurricane disasters is important for governments' long-term budgeting needs (Deryugina, 2017).

Since 1900, hurricanes striking the United States along the Gulf of Mexico have killed over 14,000 people (NOAA, n.d.*a*). However, due to better warning systems, hurricane-related deaths have decreased during the 20th century as lead time has increased from 18 to 24 hours from the time of first warning issued to the time the storm center crosses the coast (Pielke, 1999). Although lead time has increased resulting in lower death tolls, numerous studies indicate that economic losses from landfalling hurricanes are large and rising (Klotzbach et al., 2018 and Pelke Jr., R. & Pielke Sr., R., 2003). According to Weinkle et al. (2018), 197 hurricanes impacted the United States during 1900-2017, resulting in approximately $2 trillion in normalized (2018) damages. Of the 197 hurricanes that impacted the U.S., 125 (or 63%) made landfall along the Gulf Coast accounting for 72% of total U.S. hurricane damages. Fifty-one (or 40%) of the 125 hurricanes that made landfall along the Gulf Coast were major hurricanes (Category 3-5), which resulted in about $1.3 trillion (or 90%), of the total damages during the study period. These data provide an illustrious representation of the economic hardship the Gulf Coast has experienced over the last century. However, it can be argued that these numbers are not an exhaustive representation of the total losses from hurricanes. Deryugina (2017) asserts the fiscal impact of hurricanes in the U.S. is much greater once disaster aid, social safety net programs, and social insurance transfers are accounted for. In a study by Deryugina (2017) the federal government spent $19 billion on hurricane-related disaster aid during the study period 1979-2002. Due to practical constraints, this paper cannot provide a comprehensive review of normalized losses together with social safety net transfers during the long-term study period. However, it is worth pointing out that there are additional aspects that contribute to the total economic losses from hurricane landfalls which are not typically included in the hurricane-related loss estimates.

Research has argued the major factors behind increasing losses are due to inflation, population growth, and increases in wealth and property values (Pielke & Landsea, 1999; Choi & Fisher, 2003; Pielke et al., 2008; Mohleji & Pielke, 2014). While the effects of climate change on hurricanes is not yet evident, Pielke (2007) and Schmidt et al. (2009) claim that exposure growth will have a greater effect on hurricane losses in the U.S. than anthropogenic climate change. Still, as global climate change persists from anthropogenic forcings, it is likely climate oscillations, including the AMO, ENSO, and NAO, will be enhanced and have an additive effect on damages to the Gulf Coast. Thus, there is a critical role for stakeholders in evaluating and promoting sustainable development along with better mitigation practices to prepare for and lessen the devastating impacts of intensifying hurricane landfalls. To date, little research has been done to examine the relationship between climate modes, such as the AMO, ENSO, and NAO, and destructiveness from hurricane landfalls. Therefore, this study makes a major contribution to research on hurricane losses by demonstrating the relationship between hurricane frequencies and damages to specific phases of three climate indices. The following section will look at the economic impacts of hurricane landfalls to Gulf Coast states using normalized data from Weinkle et al. (2018).

Methods

Normalized hurricane damages over the study period were examined in conjunction with each climate oscillation, the AMO, ENSO, and NAO, to identify during which phase hurricane landfalls have caused the most substantial damages to the U.S. Gulf Coast. Weinkle et al. (2018) generated normalized (2018) hurricane losses in the U.S. from 1900-2017 using the base-year economic damage from each hurricane, as well as inflation, wealth per capita and population adjustments (known as the PL18 methodology). For the purpose of this study, only hurricanes that made landfall in Gulf Coast states (FL, AL, MS, LA, and TX) from the Florida Keys to Brownsville, Texas that were a Category 3 or higher at some point along their track were used. This further reduces the data to 65 total hurricanes that made landfall in the study area, 51 of which were major hurricanes (Figure 3.1). A supplementary table including the storm name/ID, year of landfall, category, state(s) impacted, base economic damages, PL18 normalized damages, and damage as a percent of state GDP can be seen in Table 2 of the Appendix.

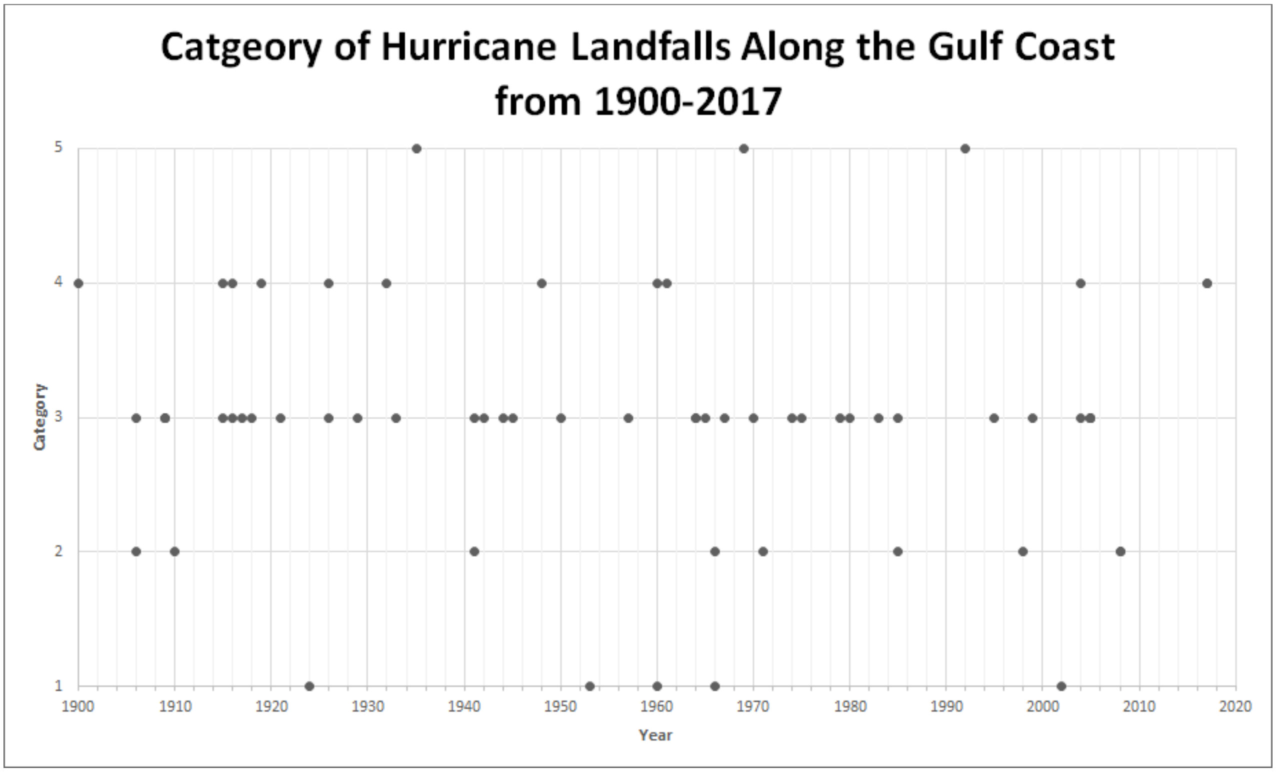

Figure 3.1 Category of Hurricane Landfalls Along the Gulf Coast from 1900-2017

Scatterplot of the category of Gulf Coast hurricane landfalls from 1900-2017.

Figures 3.2 and 3.3 shows PL18 normalized damages from all Gulf Coast hurricane landfalls and major hurricane landfalls. Interpretation of the data reveals that damages from all Gulf Coast hurricanes during the study period have increased by approximately $45 million per year, whereas major hurricane landfall damages have increased by approximately $27 million per year. Pielke et al. (2008) suggest that the trends in hurricane losses will continue to increase as wealthier people inhabit the nation's coasts that are susceptible to hurricanes destructive power.

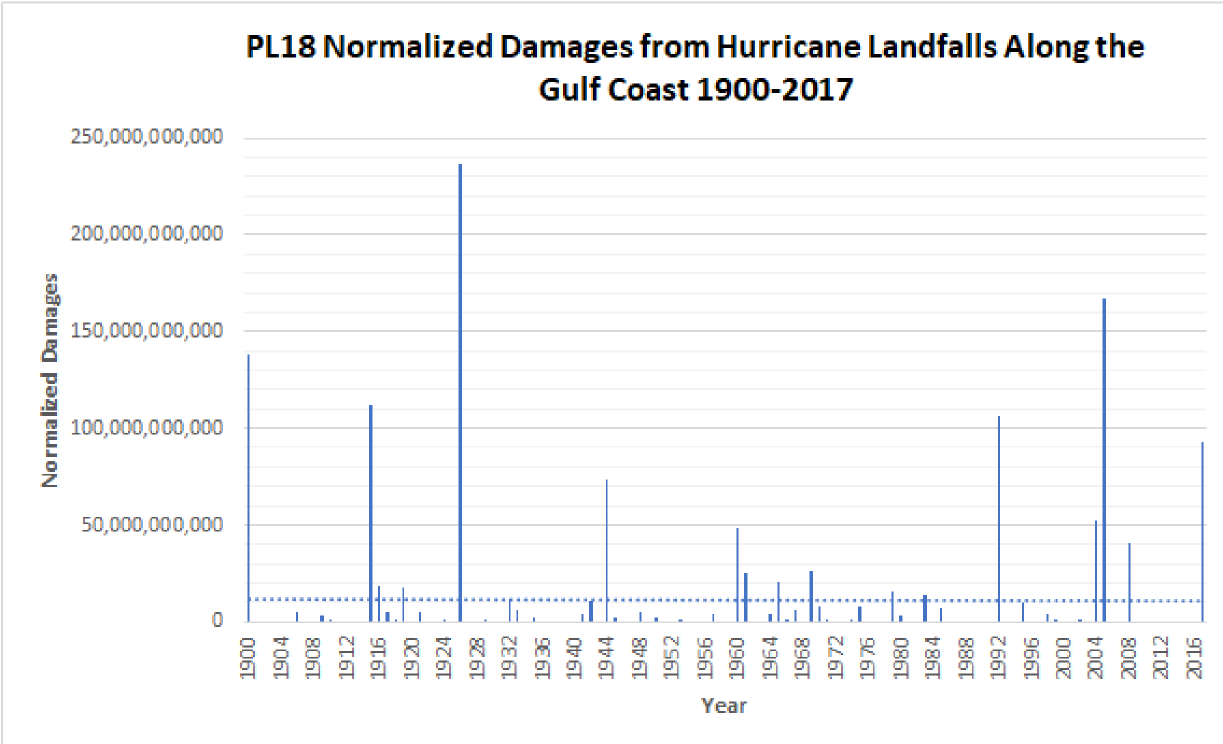

Figure 3.2 PL18 Normalized Damages

PL18 Normalized damages from hurricane landfalls along the Gulf Coast from 1900-2017. The dotted line is the linear trend over the indicated period.

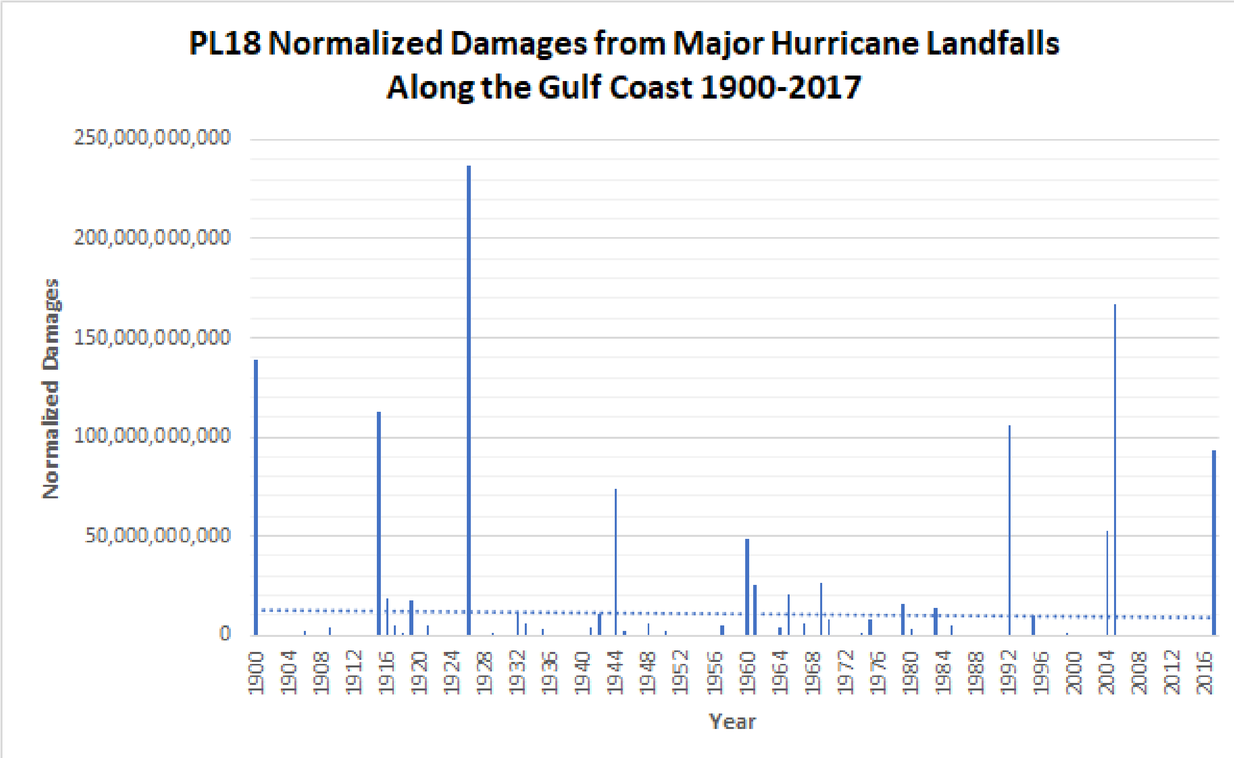

Figure 3.3 PL18 Normalized Damages (Major Hurricanes)

Normalized damages from major hurricane landfalls along the Gulf Coast from 1900-2017. The dotted line is the linear trend over the indicated period.

Teleconnection damages

According to Pielke & Landsea (1999) Atlantic hurricane landfalls in the U.S. have a strong relationship with the El Nino-Southern Oscillation (ENSO). La Nina and El Nino are the terms used to describe years of alternating sea surface temperatures and atmospheric pressure across the equatorial Pacific Ocean off the coast of South America (NOAA, 2018). The Multivariate ENSO Index (MEI) is a method used to calculate the intensity of ENSO events using 5 different variables, which are further explained by Wolter & Timlin (2011). The MEI is calculated bi-monthly (i.e. March-April, April-May, etc.). Only the MEI values from August-September and September-October were used as these months are significant to 95% of all major hurricanes (Pielke & Landsea, 1999). The Aug-Sep, Sep-Oct values were averaged to identify El Nino and La Nina years. During El Nino (positive phase), SSTs in the region of the Pacific known as Nino 3.4 (5ºN-5ºS and 120º-170ºW) are greater than or equal to 0.4º C warmer than the long-term average during August, September, and October (ASO). During La Nina (negative phase), SSTs in Nino 3.4 are greater than or equal to 0.4º C cooler during ASO (Pielke & Landsea, 1999). Neutral years are all other years when neither La Nina or El Nino conditions are present. It should be noted that NOAA defines Nino 3.4 SST anomalies up to +/-0.5º C. However, given that normalized (PL18) hurricane damage data from Pielke is used throughout this study, the +/-0.4º C value presented in Pielke & Landsea (1999) was used in this study. The 65 hurricanes in the dataset were grouped according to the phase of ENSO in which they made landfall. Finally, the costs of all hurricanes that occurred during each phase were totaled.

For the 118-year period examined in this paper, there have been 39 El Nino years and 40 La Nina years, with the other 39 years being neutral (Figure 3.4).

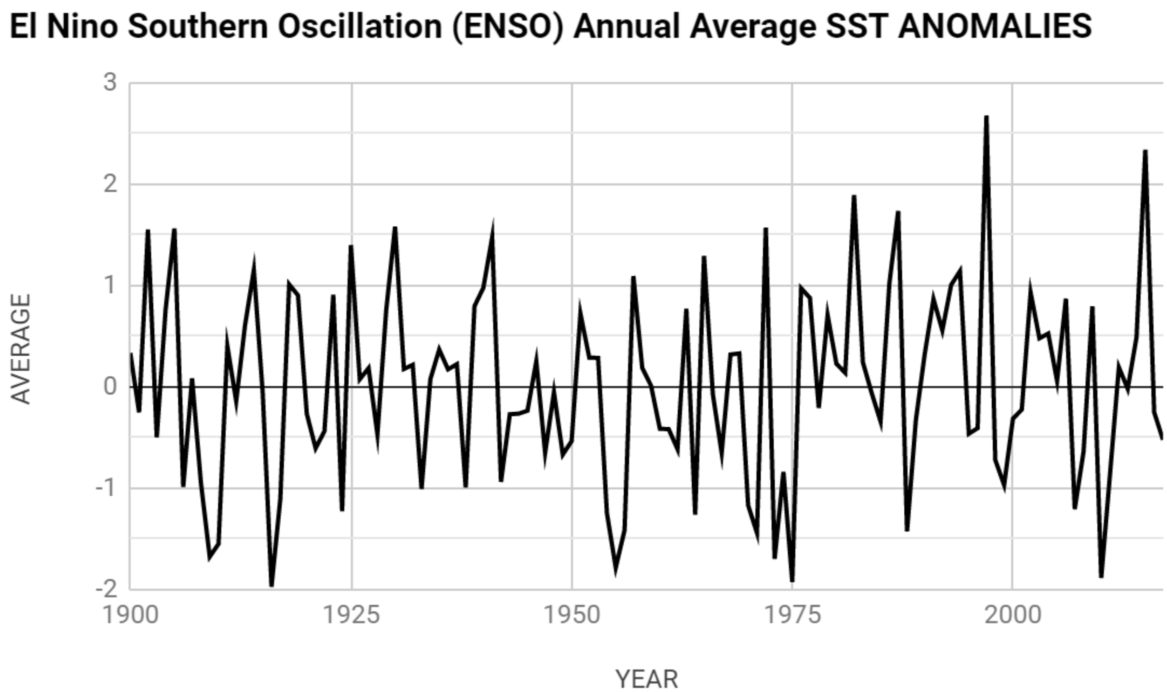

Figure 3.4 ENSO Annual Average SST Anomalies

Average SST anomalies during ENSO for the months of August, September, and October from 1900-2017.

Gray (1984) found a 3:1 ratio in U.S. landfalling hurricanes with 74% per year striking during non-El Nino years and only 25% per year during El Nino years. In particular, La Nina years exhibit significantly higher hurricane losses compared to El Nino years (Pielke & Landsea, 1999). During La Nina, weaker upper-level westerly winds & lower-level easterly winds reduce vertical wind shear and decrease atmospheric stability, which favors the development of hurricanes in the Atlantic, Caribbean and Gulf of Mexico (L'Heureux et al., 2014).

An analysis of damages from Gulf Coast landfalling hurricanes during El Nino, La Nina and neutral years is shown in Figures 3.5, 3.6, and 3.7. The data reveals there were 12 hurricane landfalls during El Nino years, 31 during La Nina years, and 22 during neutral years. There were some years during each phase that had multiple landfalls and damages were totaled for those years. The total cost of normalized damages during El Nino were approximately $225 billion (Figure 3.5), $310 billion during La Nina (Figure 3.6), and $800 billion during neutral years (Figure 3.7). Seemingly, the damages were not significantly different during La Nina and El Nino years given the considerable difference in number of landfalls during each phase. This is likely due to Hurricane Andrew's $106 billion in normalized damages that occurred during an El Nino year. While Andrew was a rather small, compact storm, the sustained winds up to 165 mph accounted for most of the damage to southern Florida, making it the second costliest storm in U.S. history after Hurricane Katrina (2005) (Sarkis, S., 2017). If Andrew is removed from the analysis, the resulting damages during La Nina years come to be over 2.5 times more than El Nino years, corresponding to the difference between the number of landfalls during the two phases. Still, damages during neutral years were highest, being more than 2.5 times higher than La Nina years and over 3.5 times higher than El Nino years. These findings closely support the research by Gray (1984) regarding the ratio of U.S. hurricane landfalls during El Nino and non-El Nino years. Our findings are slightly higher, however, given the study area is specific to the Gulf Coast rather than the United States altogether. The data show that 82% of landfalls to the study region occurred during non-El Nino years, whereas only 18% of landfalls occurred during El Nino years.

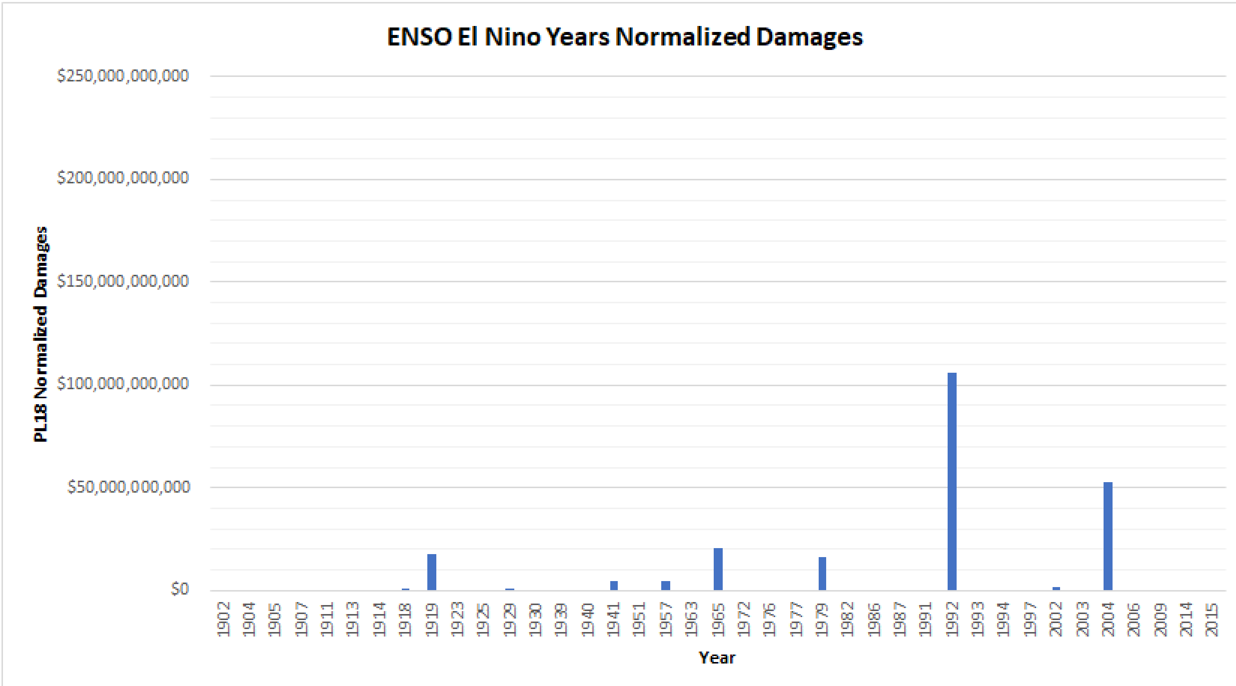

Figure 3.5 ENSO El Nino Normalized Damages

PL18 normalized damages from hurricane landfalls during the positive years of ENSO.

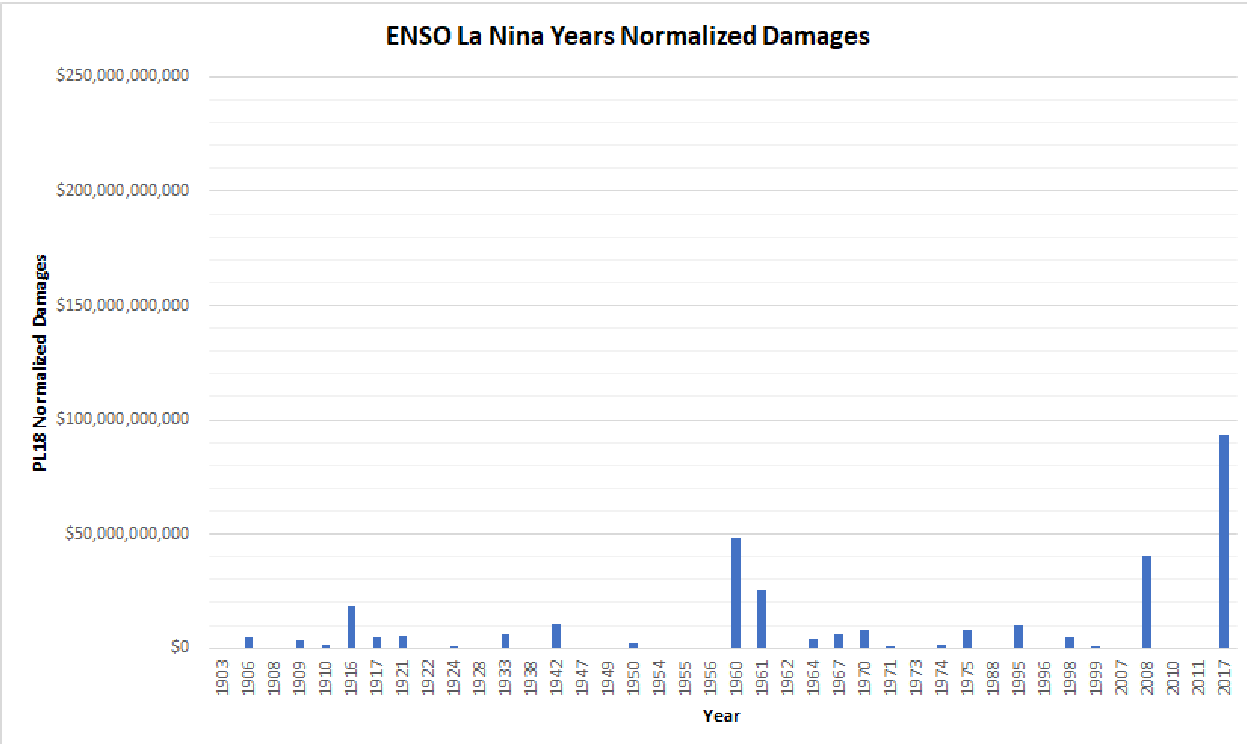

Figure 3.6 ENSO La Nina Normalized Damages

PL18 normalized damages from hurricane landfalls during the negative years of ENSO.

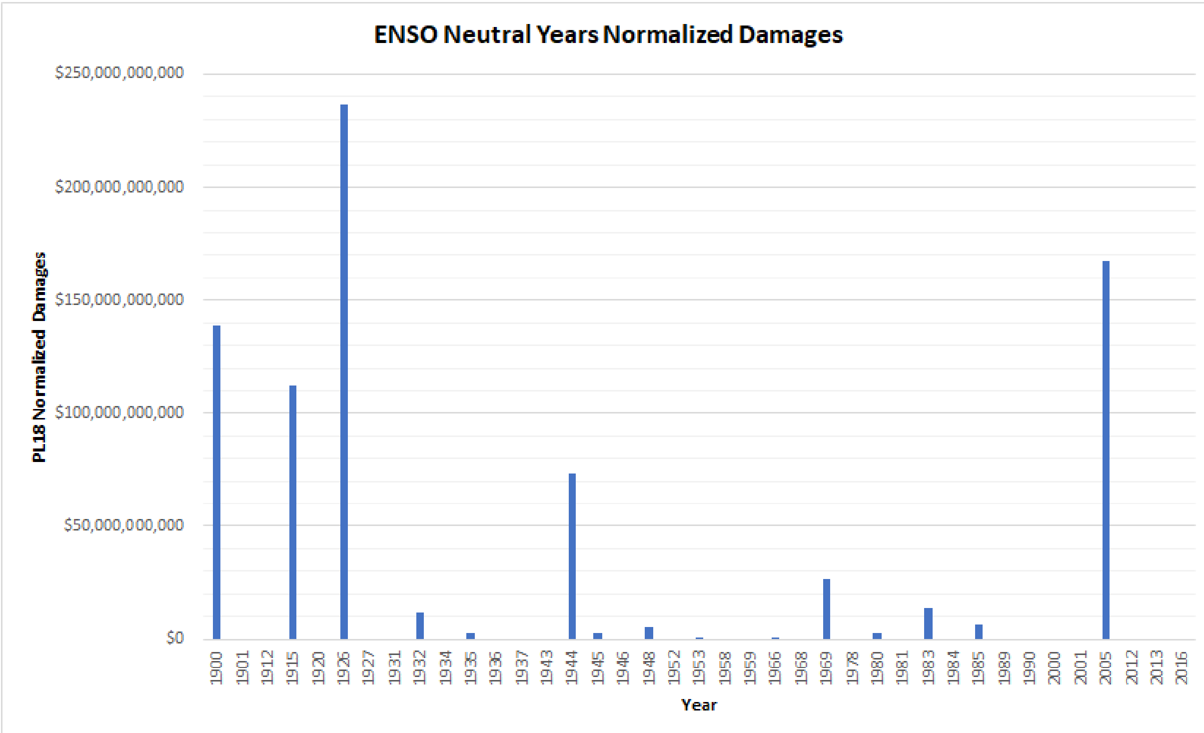

Figure 3.7 ENSO Neutral Phase Normalized Damages

PL18 normalized damages from hurricane landfalls during the neutral years of ENSO.

In order to examine the relationship between major hurricane (MH) occurrences during ENSO phases, Category 1-2 hurricanes were removed from the data. In doing so, similar results to the analysis including all hurricane categories are seen, with 80% of landfalls during non-El Nino years and 20% during El Nino years. Out of the total 65 hurricane landfalls, 51 were major hurricanes: 10 that made landfall during El Nino years, 23 during La Nina years, and 18 during neutral years. Damages that resulted during El Nino years totaled about $220 billion (Figure 3.8), over $250 billion during La Nina (Figure 3.9), and approximately $800 billion during neutral years (Figure 3.10). Again, the damages during El Nino and La Nina are not largely different given there were 13 more MHs to make landfall during La Nina years. However, if Hurricane Andrew is removed from the analysis, the damages during La Nina years come to be more than twice as much as damages that resulted during El Nino years, coinciding with the difference between number of landfalls. Though, neutral years still show the highest damages, with about 3 times as much as La Nina year damages and over 3.5 times more than El Nino year damages. These findings are valuable in providing stakeholders with a better understanding of risk based upon climate variability. Furthermore, this analysis can be used to set aside supplementary funds for hurricane-related losses during the years that are identified as more active (Pielke & Landsea, 1999).

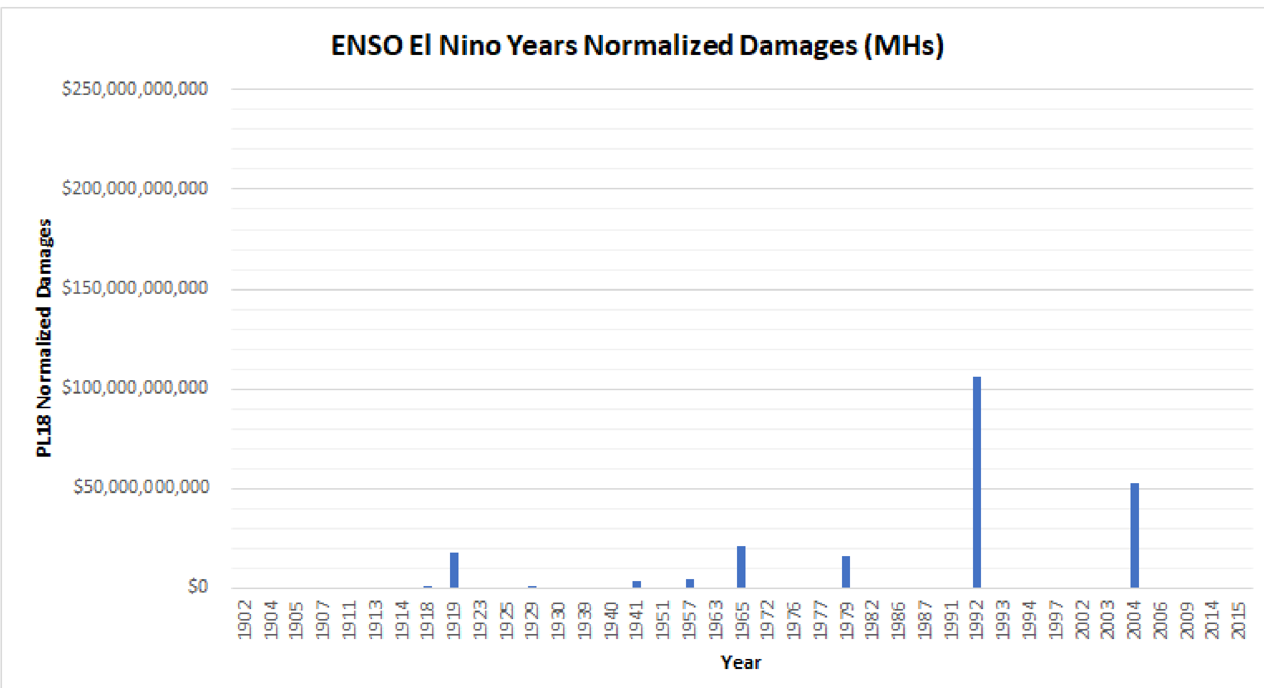

Figure 3.8 ENSO El Nino Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the positive years of ENSO.

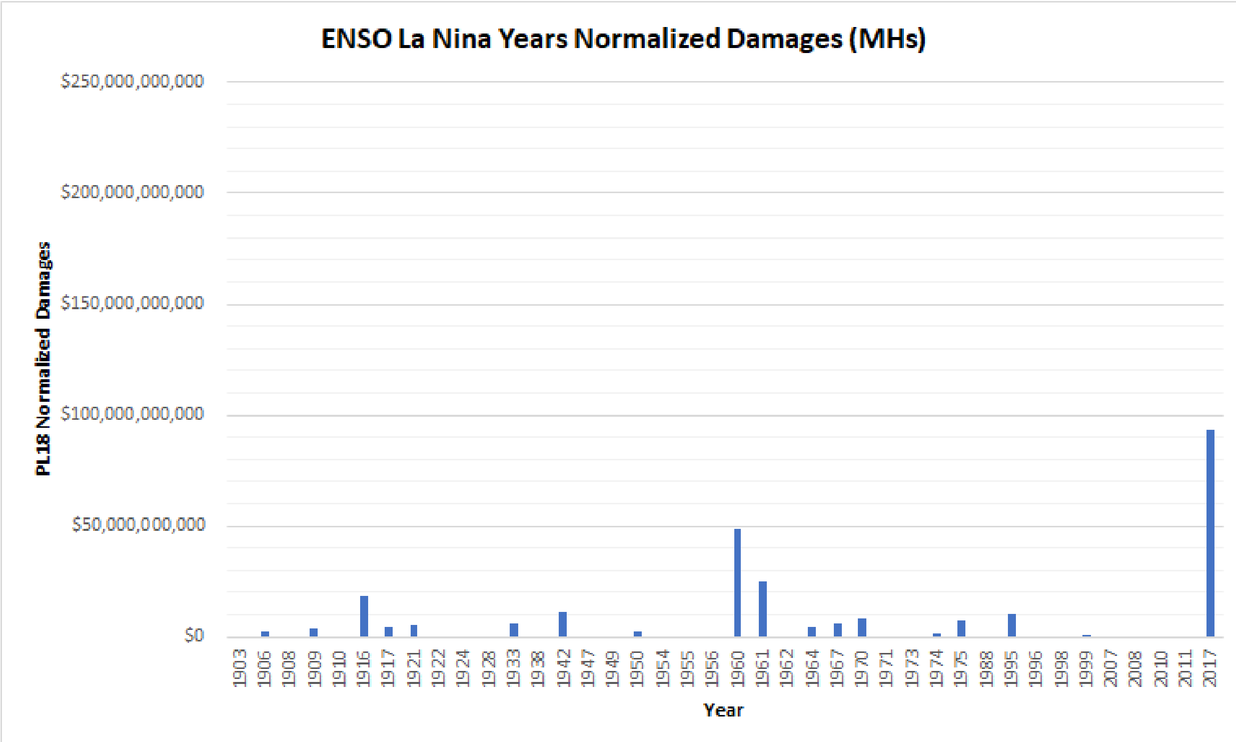

Figure 3.9 ENSO La Nina Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the negative years of ENSO.

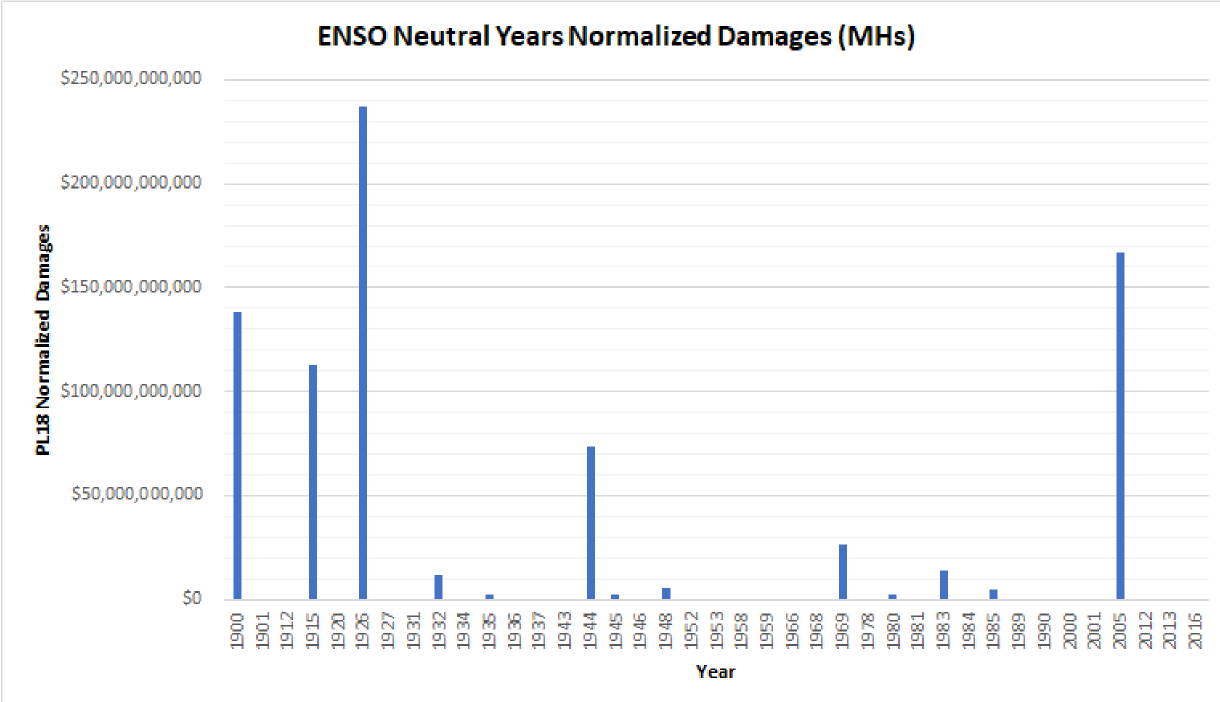

Figure 3.10 ENSO Neutral Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the neutral years of ENSO.

The North Atlantic Oscillation (NAO) is another mode of climate variability that was analyzed in an effort to identify if a relationship exists between the occurrence of hurricane landfalls and destructiveness along the Gulf Coast and, a specific phase of the teleconnection. The NAO is a result of the difference in the Subtropical Azores High and the Subpolar Icelandic Low (NOAA, n.d.*b*). The NAO can occur on yearly or decadal timescales (Figure 3.11).

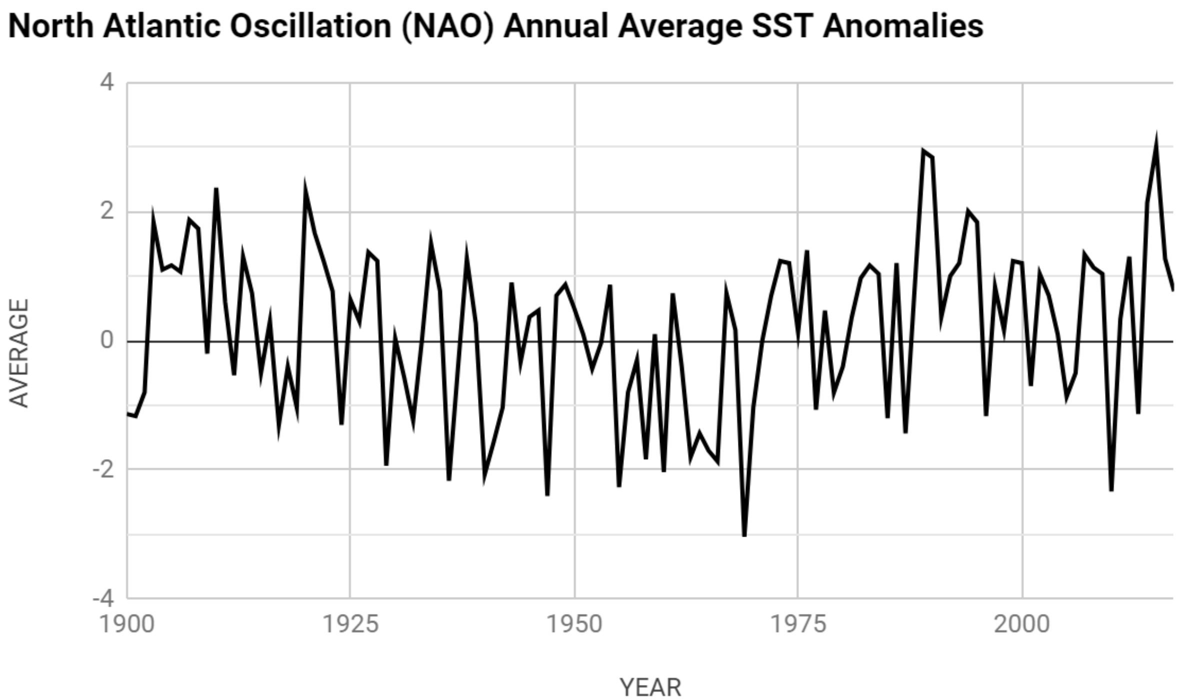

Figure 3.11 NAO Annual Average SST Anomalies

Average SST anomalies during the NAO for the months of January, February and March from 1900-2017.

During the positive phase of the NAO, the Subpolar low and Subtropical High are stronger than normal, resulting in a stronger jet stream and northward shift of storm tracks (Dahlman, 2009). Conversely, the opposite conditions occur during the negative phase, resulting in a more west-to-east flow of the jet stream bringing lower pressure and increased storminess to eastern North America (Dahlman, 2009). Research has linked the NAO index to the tracks taken by major Atlantic hurricanes (Elsner et al., 2000). According to Elsner et al. (2000), the Gulf Coast is more susceptible to a major hurricane strike during a negative NAO. This occurs when the Azores High weakens and shifts south and west, near the Caribbean. The high-pressure ridge over the western North Atlantic impedes hurricanes from curving northward. Thus, storms remain over warm, tropical waters for a longer period of time and are conducive to making landfall in the Gulf of Mexico (Elsner et al., 2000). Additionally, negative sea level pressure and positive SST anomalies over the subtropical Atlantic during the negative phase, provide very favorable conditions for hurricane genesis over the region (Lim et al, 2016).

An analysis was conducted to identify any trends related to the occurrence of Gulf Coast hurricanes and the NAO. Figures 3.12 and 3.13 show the associated damages from hurricane landfalls during the negative and positive phases. Out of the 65 total hurricanes that made landfall in the study area, 30 made landfall during the positive phase of the NAO and 35 made landfall during the negative phase. The resulting damages from landfalls during the positive phase amounted to approximately $650 billion (Figure 3.12), whereas damages during the negative phase totaled roughly $685 billion (Figure 3.13). These findings do not provide enough data to predict the likelihood of hurricane landfalls in the study area during one phase over another.

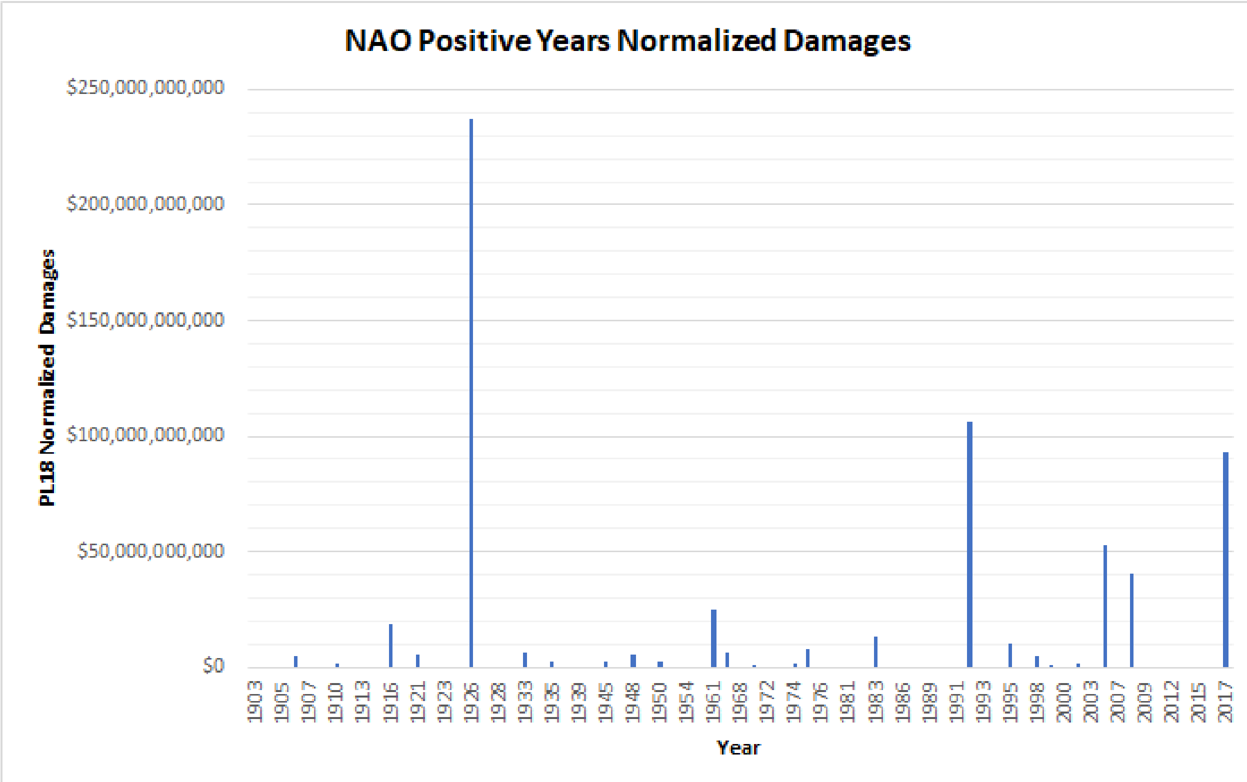

Figure 3.12 NAO Positive Phase Normalized Damages

PL18 normalized damages from hurricane landfalls during the positive years of the NAO.

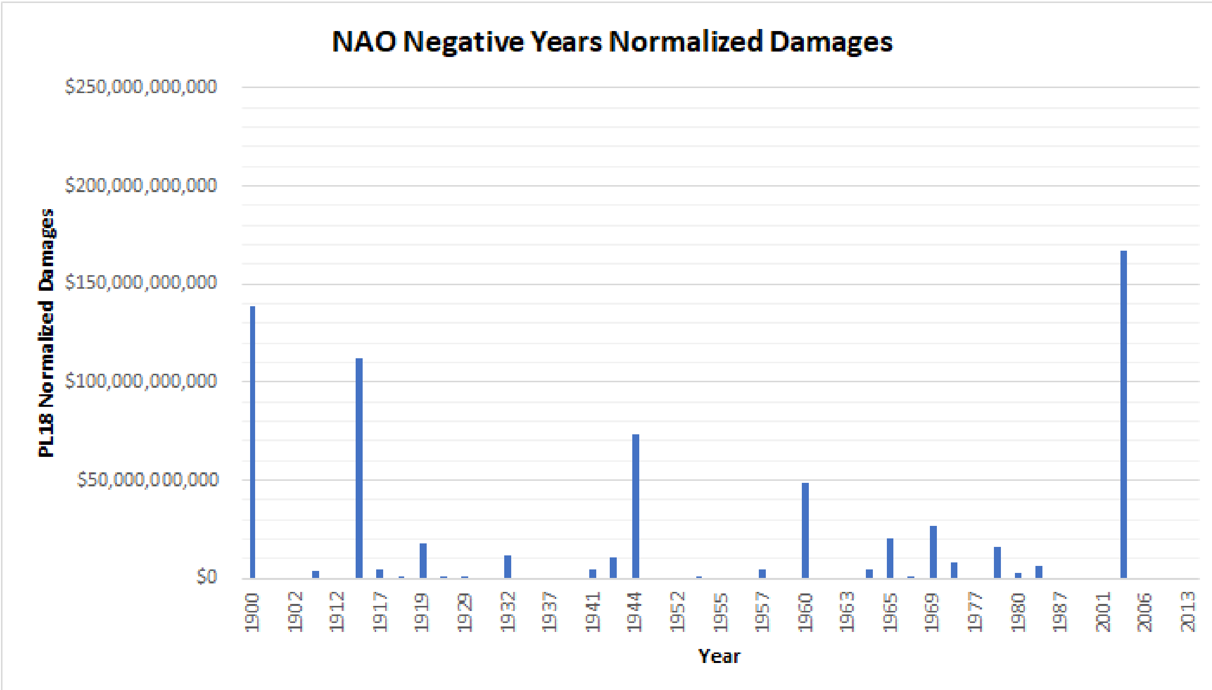

Figure 3.13 NAO Negative Phase Normalized Damages

PL18 normalized damages from hurricane landfalls during the negative years of the NAO.

To evaluate major hurricane landfalls during the NAO, Category 1 and 2 hurricanes were removed from the analysis and the number of MH occurrences and associated damages during each phase were compared. The findings show that 23 (or 77%) of hurricanes that made landfall during the positive phase of the NAO were MHs, while during the negative phase, 28 (or 80%) of landfalls were MHs. The associated damages during the positive phase added up to roughly $600 billion. During the negative phase, damages amounted to approximately $680 billion (Figures 3.14 and 3.15).

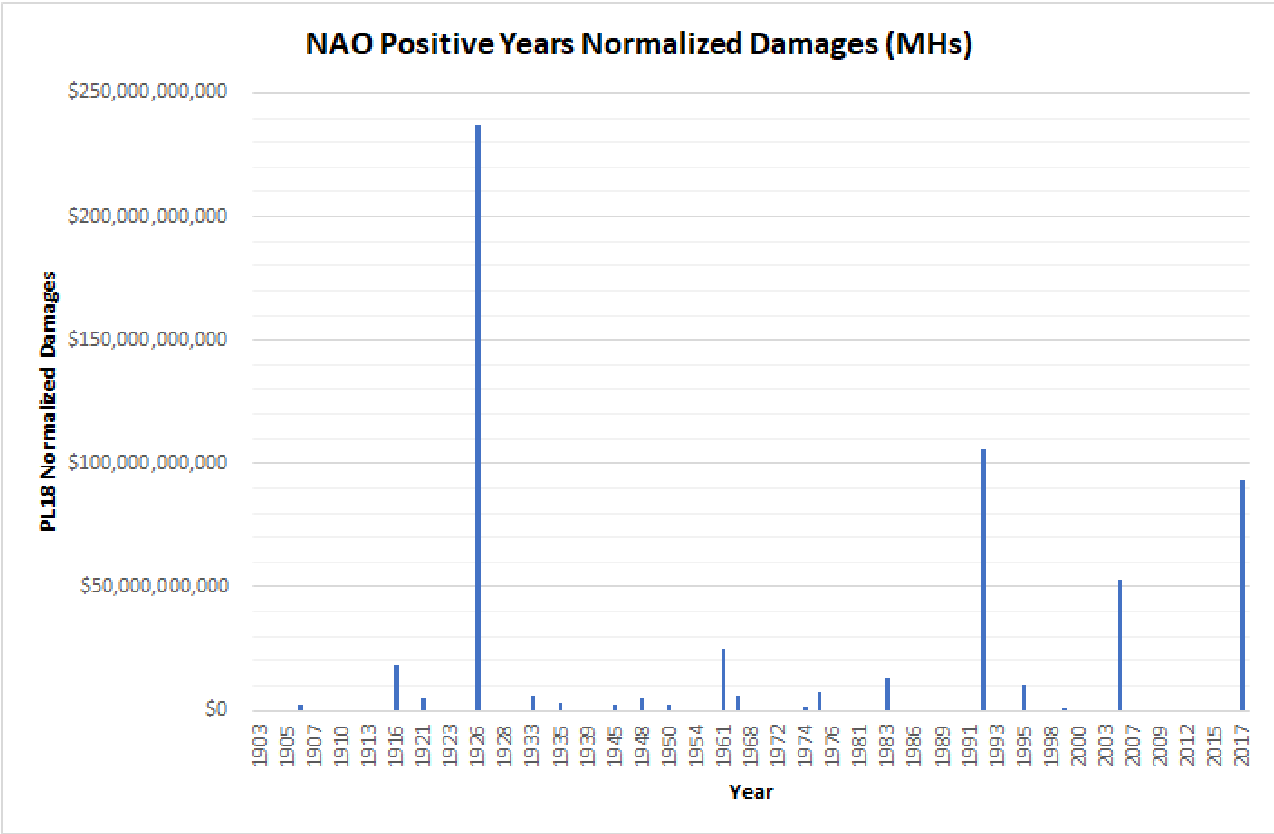

Figure 3.14 NAO Positive Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the positive years of the NAO.

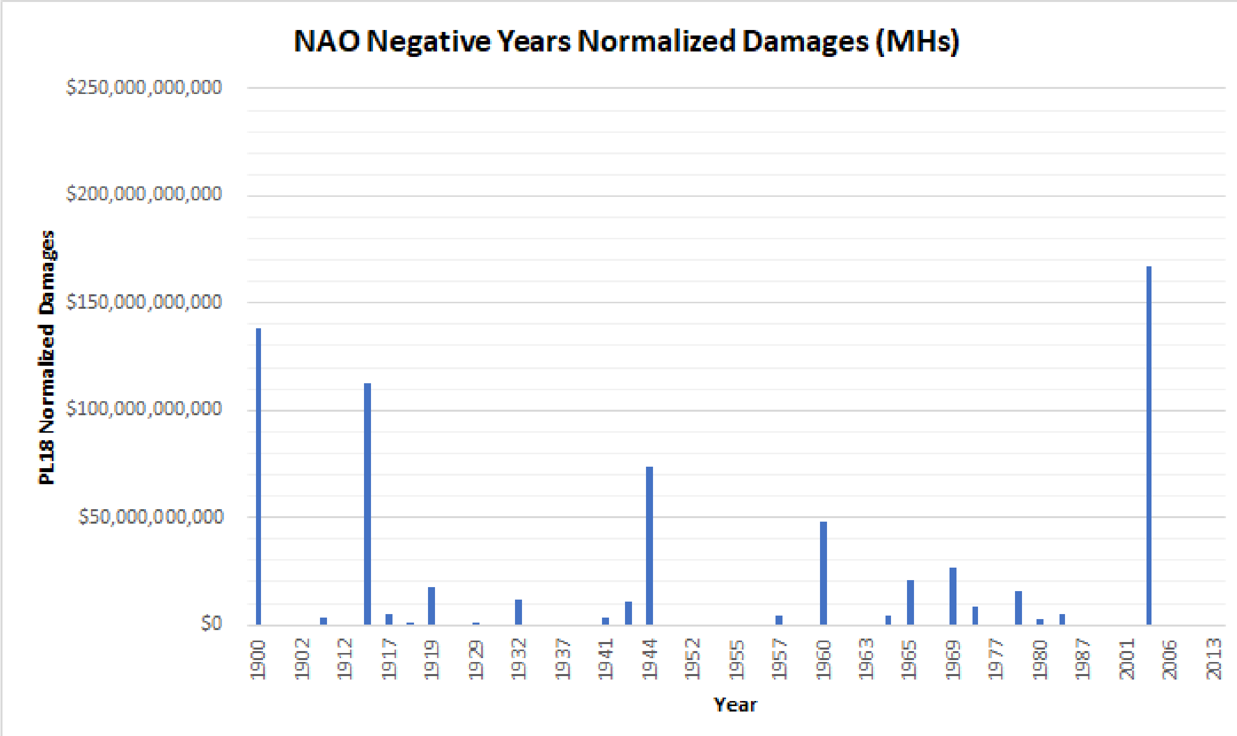

Figure 3.15 NAO Negative Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the negative years of the NAO.

While there is a slightly higher number of MHs and associated damages during the negative phase of the NAO, the findings establish there is not a significant difference in the data to suggest the probability of an MH occurrence during one phase over the other.

Given the insignificant differences between landfalls during the positive and negative phases, the data was narrowed to only the 20 most positive and negative years of the January, February and March average. In doing so, there is a more pronounced difference in the number of landfalls and associated damages. During the positive phase, there were only 3 years that a hurricane made landfall in the study area. The damages from these 3 landfalls was roughly $16.5 billion (Figure 3.16). Out of the highest averages for the negative phase, there were 11 years in which a hurricane made landfall in the study area, including some years which had multiple landfalls. The 16 total landfalls amounted to approximately $130 billion in damages (Figure 3.17), clearly illustrating the impact of a strong, negative NAO on the Atlantic hurricane season.

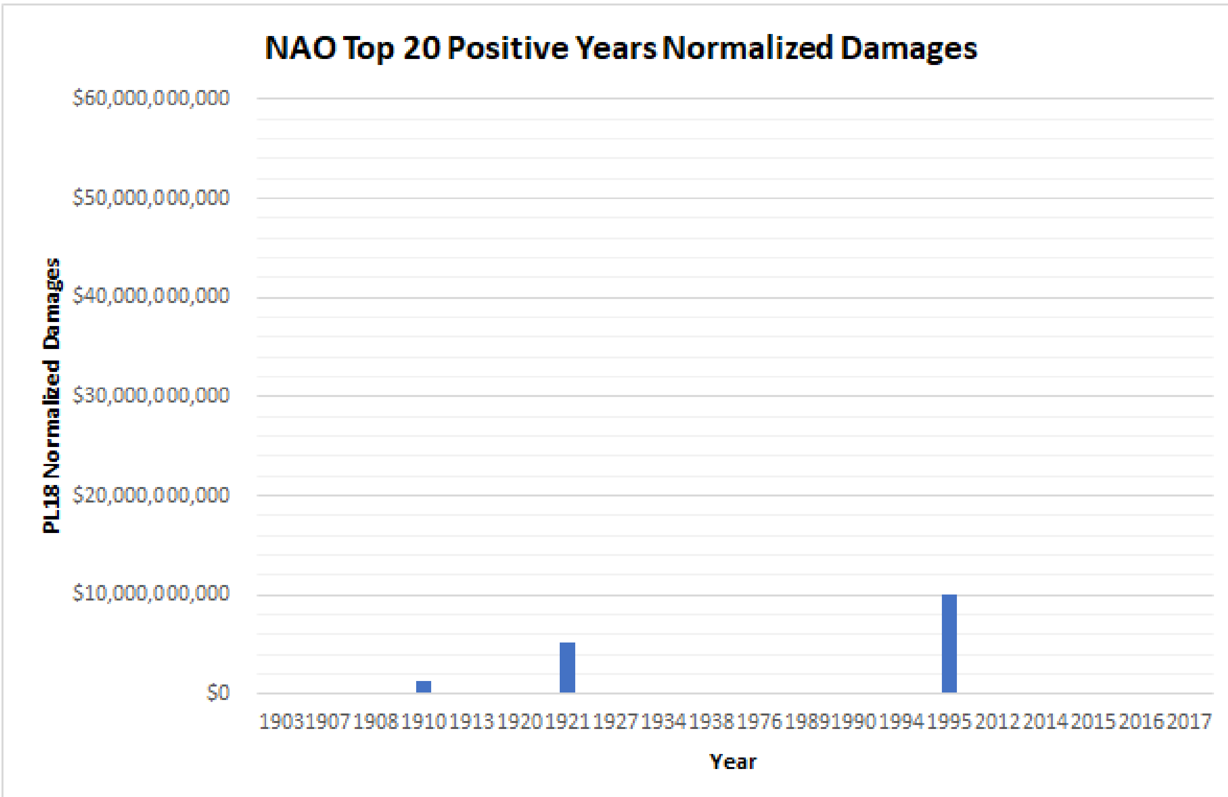

Figure 3.16 NAO Top Positive Phase Normalized Damges

PL18 normalized damages from hurricane landfalls during extreme positive years of the NAO.

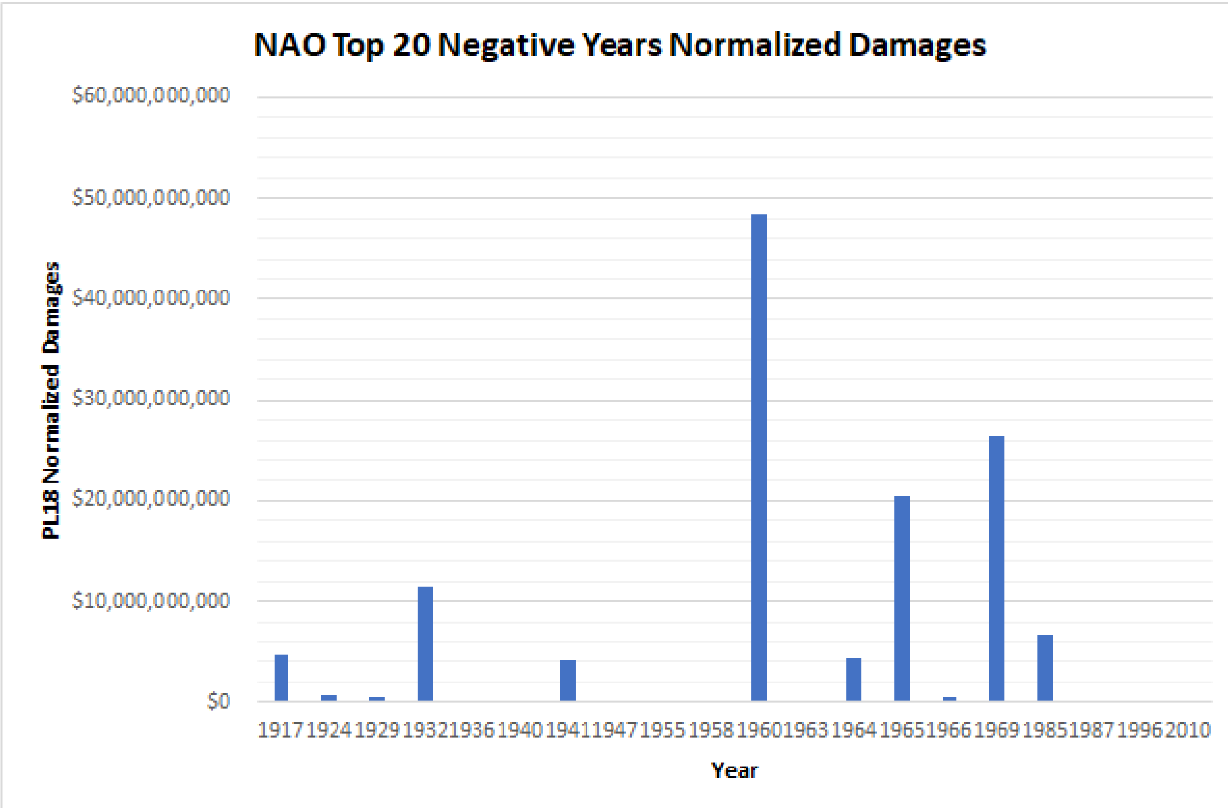

Figure 3.17 NAO Top Negative Phase Normalized Damages

PL18 normalized damages from hurricane landfalls during extreme negative years of the NAO.

Out of the 3 landfalls that occurred during the extreme positive phase years, 2 were major hurricanes which had damages of approximately $15 billion (Figure 3.18). During the extreme negative phase years, there were 10 major hurricane landfalls out of the 16 which added up to almost $125 billion (Figure 3.19).

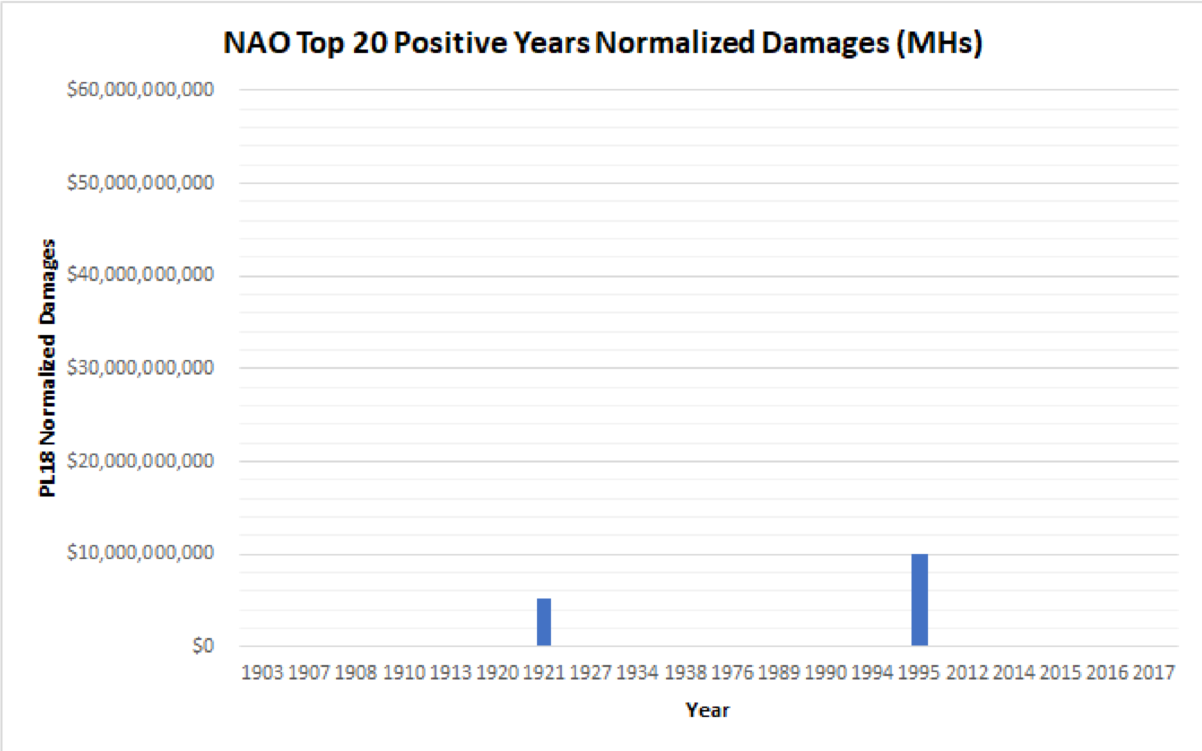

Figure 3.18 NAO Top Positve Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the extreme positive years of the NAO.

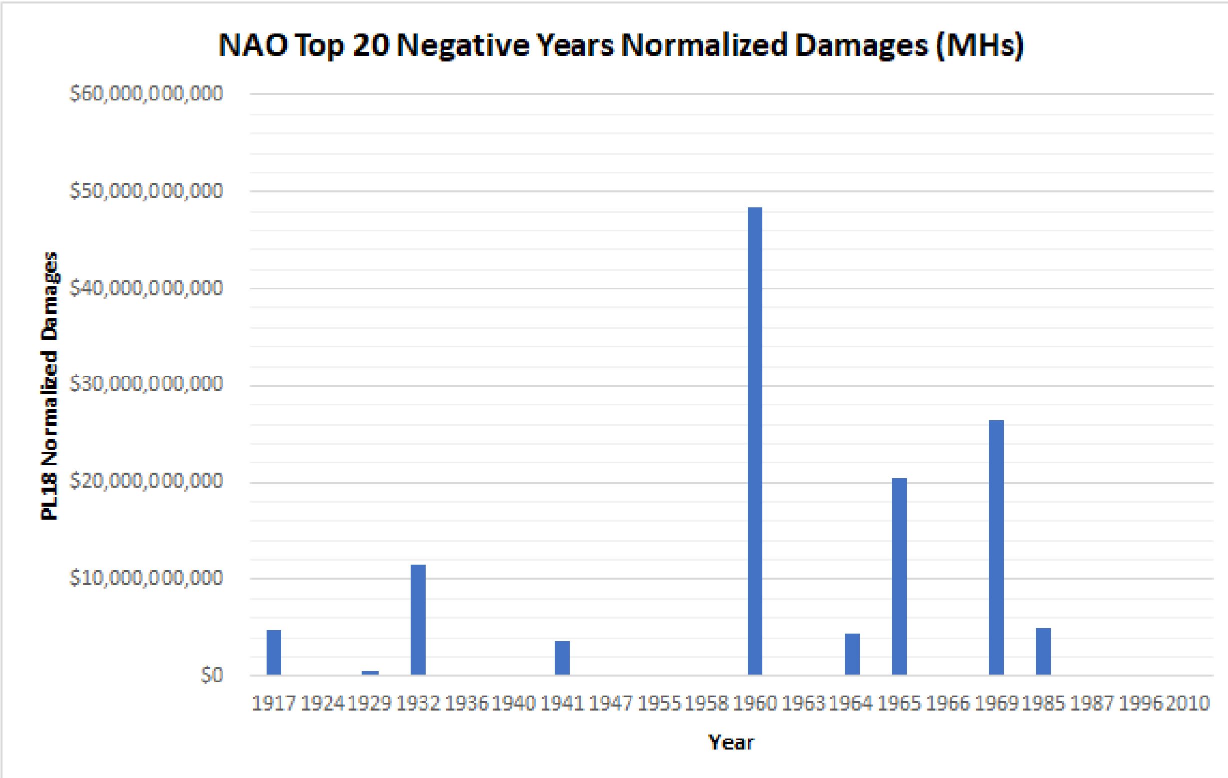

Figure 3.19 NAO Top Negative Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the extreme negative yeas of the NAO.

As revealed by this analysis, there were over 5 times as many landfalls during strong, negative NAO years which resulted in almost 8 times as much damage compared to positive years. These findings can guide climate scientists in monitoring the strength of the NAO. Thus, notable negative SST anomalies associated with the NAO during the months of January-March can help Gulf Coast residents and other stakeholders in preparing for the heightened chance of a hurricane landfall in the summer and fall months.

The last teleconnection analyzed is the Atlantic Multidecadal Oscillation (AMO). The AMO is defined as a natural variability between warm and cool phases of SSTs in the North Atlantic which affects temperature and rainfall in the Northern Hemisphere (Trenberth et al., 2019). The AMO has currently been in the warm phase since 1995 and previously during the period 1926-1969. The AMO was in the cool phases for 1900-1925, and again during 1970-1994 (Figure 3.20).

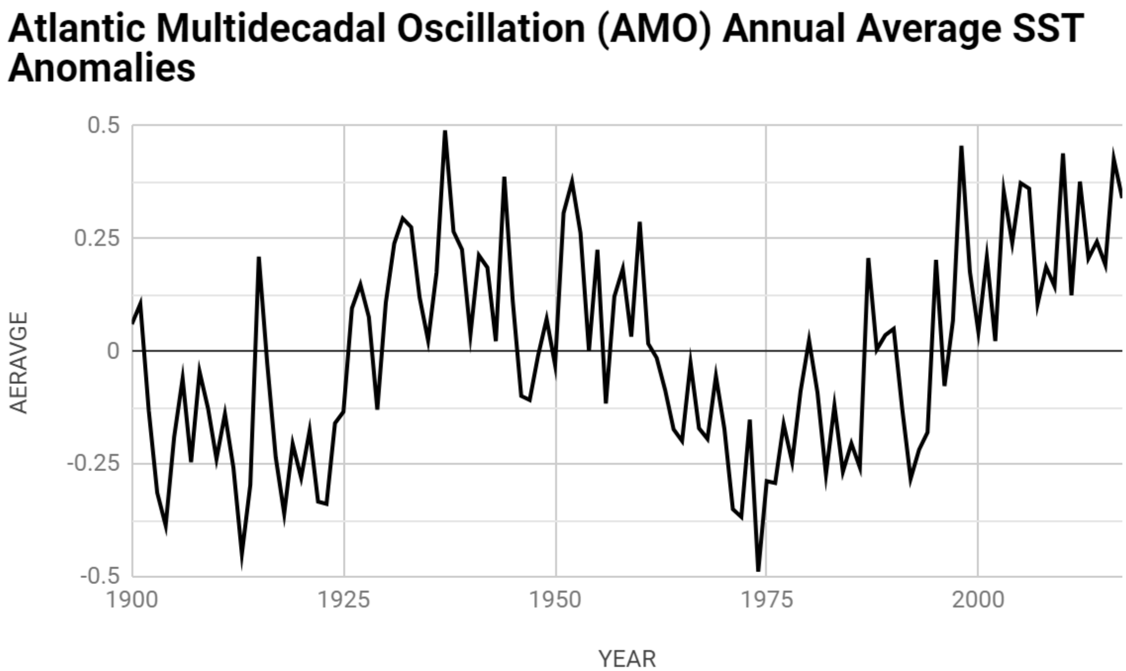

Figure 3.20 AMO Annual Average SST Anomalies

Average SST anomalies during the AMO for the months of June through October from 1900-2017.

The AMO develops from changes in circulation patterns in the Atlantic Ocean. It has been suggested that a faster thermohaline circulation is associated with warmer SSTs in the North Atlantic (Goldenberg et al., 2001). Additionally, the AMO has been linked to multidecadal precipitation variability over the Sahel region during the 5-month rainy season of June-October (O'Reilly et al., 2017). During the positive phase of the AMO, there is a large increase in precipitation over the Sahel region, which brings moist maritime air to the U.S.

(O'Reilly et al., 2017). Additionally, there are anomalously low sea level pressures and warmer SSTs sea surface temperatures in the main development region (MDR), which includes the tropical North Atlantic, Gulf of Mexico and Caribbean Sea (O'Reilly et al., 2017). Zao et al. (2009) indicated that differential warming in the Atlantic MDR is caused by changes in vertical wind shear, which is strongly correlated to atmospheric stability. Atlantic major hurricanes correspond to a large negative change in wind shear, which favors the intensification of tropical cyclones into major hurricanes (Wang et al., 2008). These anomalous conditions over the tropical North Atlantic result in 3-5 times more major hurricanes than during the negative phase of the AMO (Klotzbach et al., 2018). Therefore, an analysis of hurricane activity in the Gulf of Mexico coinciding with the positive phase of the AMO is an integral part in better forecasting the likelihood of major hurricane landfalls along the Gulf Coast.

Given the AMO is correlated to the Sahel rainy season of June through October, the SST anomaly averages of these five months was analyzed to determine the number of landfalls and associated destructiveness during the positive and negative phases. Out of the 65 total landfalls during the study period, 33 hurricanes made landfall during the positive phase while 32 landfalls occurred during the negative phase. The number of landfalls does not suggest that one phase is prone to a higher frequency of hurricane landfalls than the other. However, when the associated damages are accounted for, there is a notable difference in the cost of these landfalls, suggesting a higher strength of hurricanes during the positive phase. The normalized cost of the 33 landfalls during the positive phase amounted to over $1.050 trillion (Figure 3.21), while the total cost from the 32 landfalls during the negative phase was only approximately $283 billion (Figure 3.22), a little less than a quarter of the positive phase damages. The large variation in damages between phases can likely attributed to the four years during the neutral phase that had exceptional damages exceeding $100 billion, whereas the negative phase did not have any years amounting $100 billion.

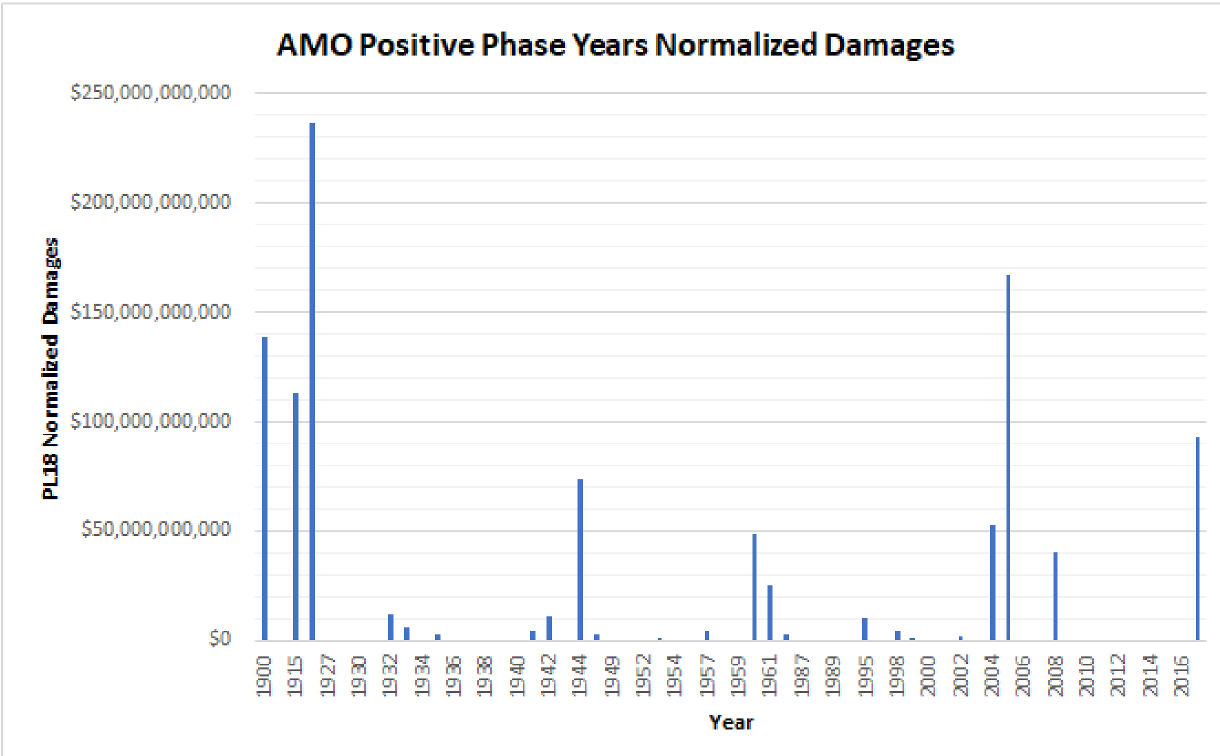

Figure 3.21 AMO Positive Phase Normalized Damages

PL18 normalized damages from hurricane landfalls during the positive years of the AMO.

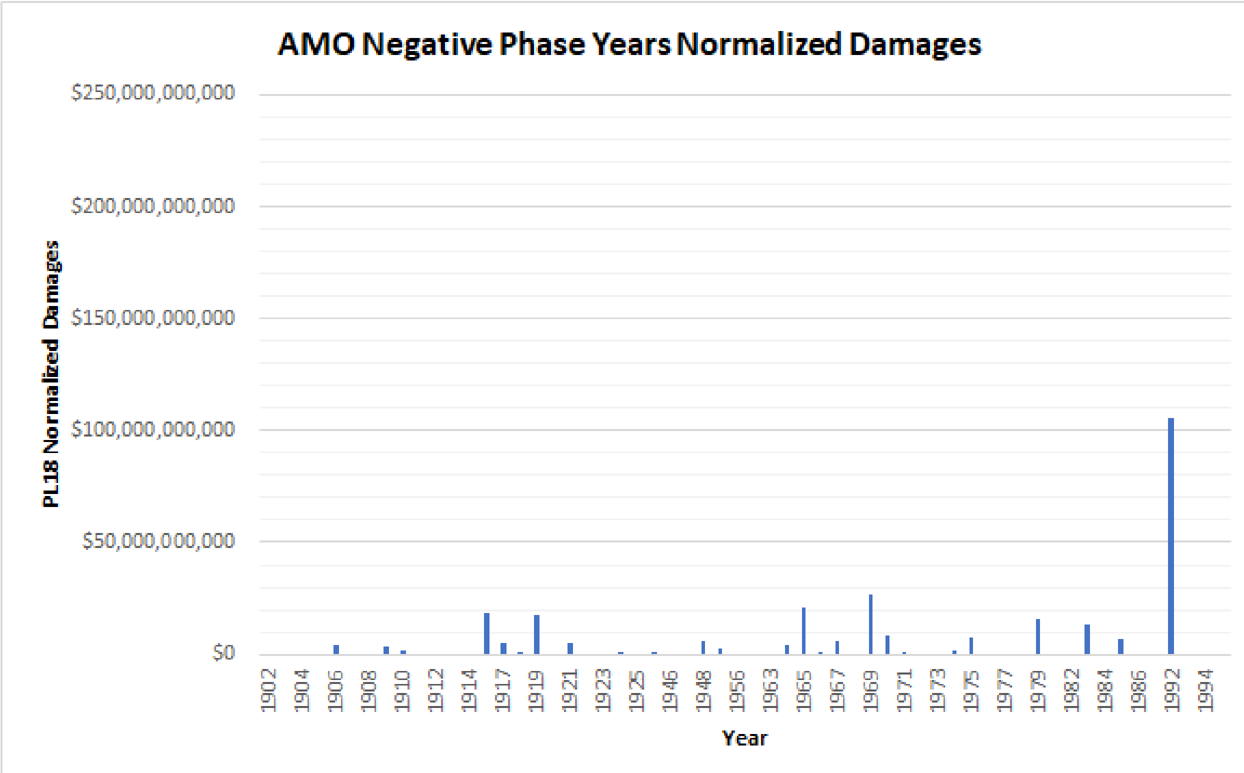

Figure 3.22 AMO Negative Phase Normalied Damages

PL18 normalized damages from hurricane landfalls during the positive years of the AMO.

Category 1 and 2 hurricanes were removed from the analysis to evaluate the number of major hurricanes that made landfall during each phase of the AMO. The data revealed 26 MH landfalls during the positive phase which added up to $1.002 trillion (Figure 3.23). During the negative phase, there were 25 MH landfalls which amounted to just $276 billion (Figure 3.24). The damages from MHs that made landfall during the positive phase are over 3.5 times more than the damages from MH landfalls during the negative phase.

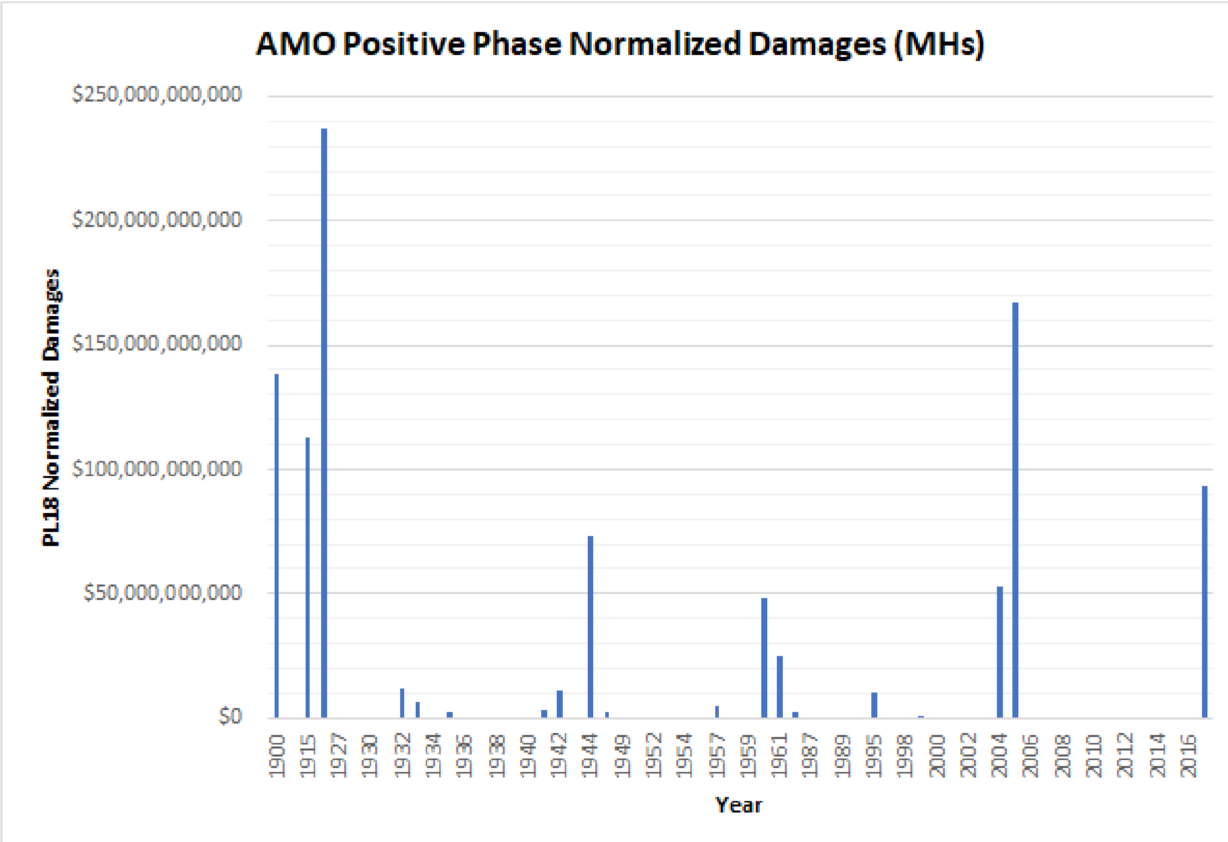

Figure 3.23 AMO Positive Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the positive phase of the AMO.

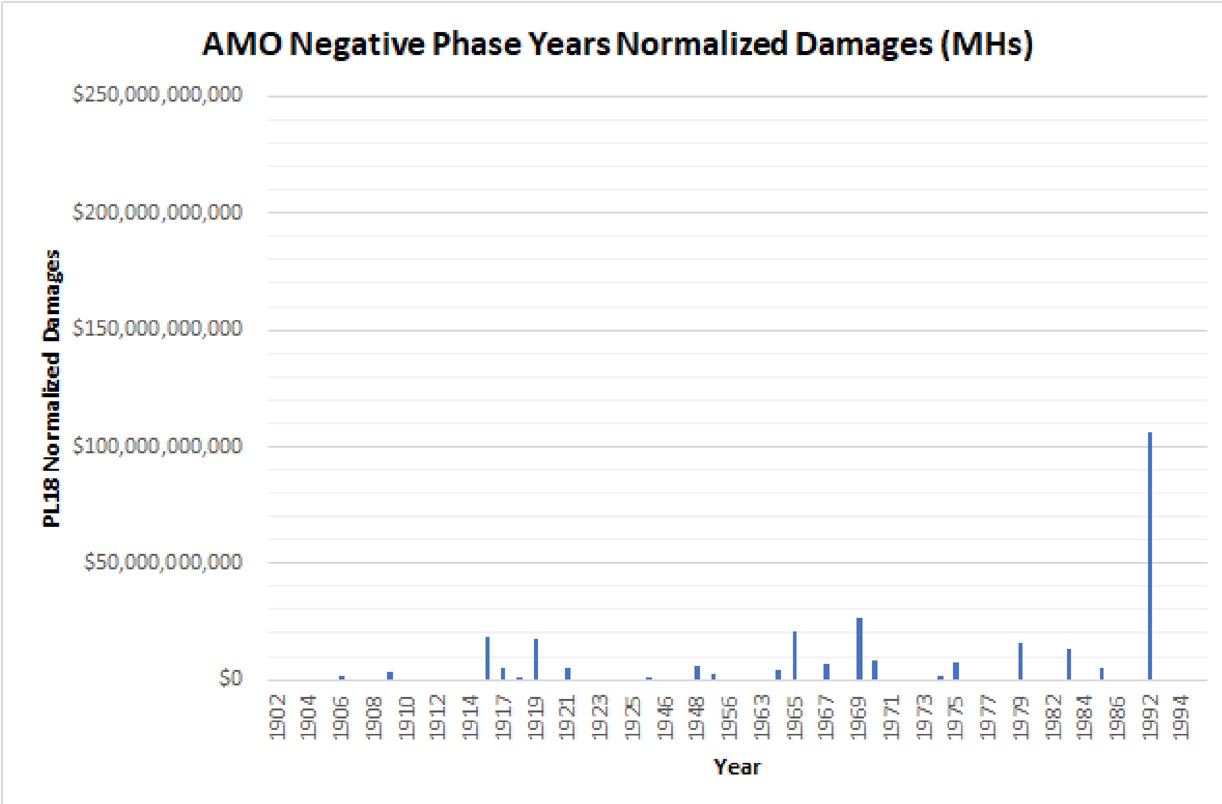

Figure 3.24 AMO Negative Phase Normalized Damages (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the negative years of the AMO.

To get a more comprehensive view of the AMO's effect on hurricane landfalls in the Gulf of Mexico, the 12-month SST anomaly average was considered (Figure 3.25).

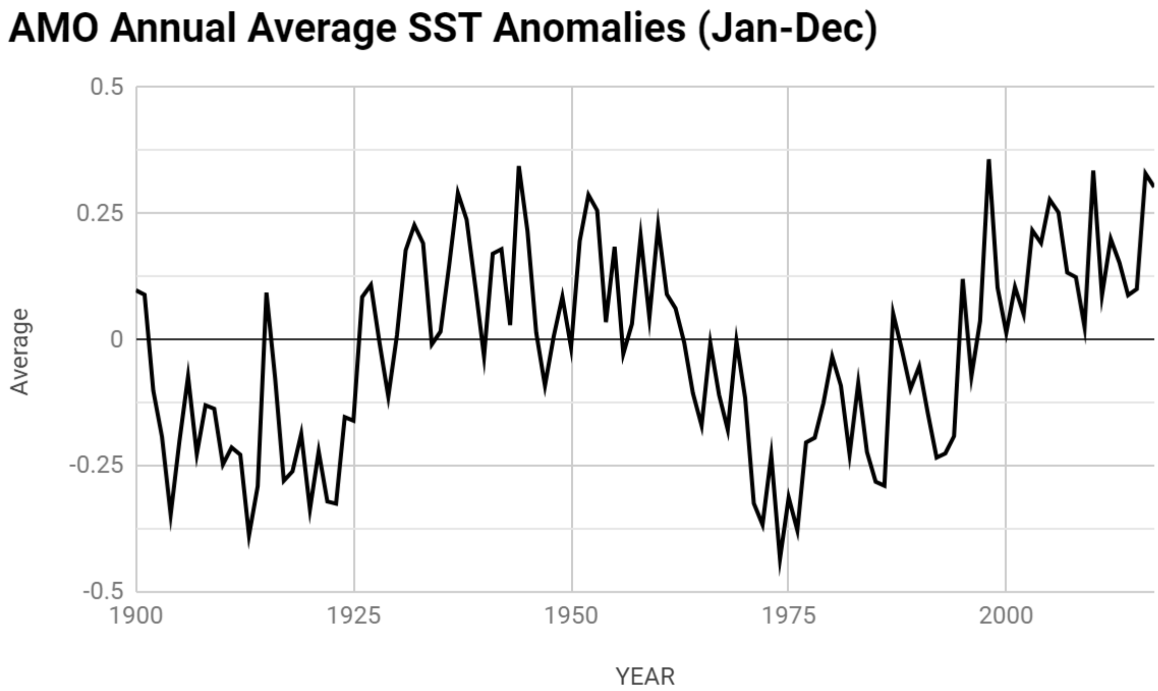

Figure 3.25 AMO Annual Average SST Anomalies [January-December]

Average SST anomalies during the AMO for the months of January through December from 1900-2017.

The data revealed the same number of landfalls during the positive and negative phases for all hurricanes and major hurricanes, but there was a slight difference in the cost of damages. Overall, the positive phase showed significantly higher damages than the negative phase, even though the number of landfalls was almost the same. The positive phase damages amounted to $1.053 trillion (Figure 3.26), while the negative phase damages were roughly $280 billion (Figure 3.27).

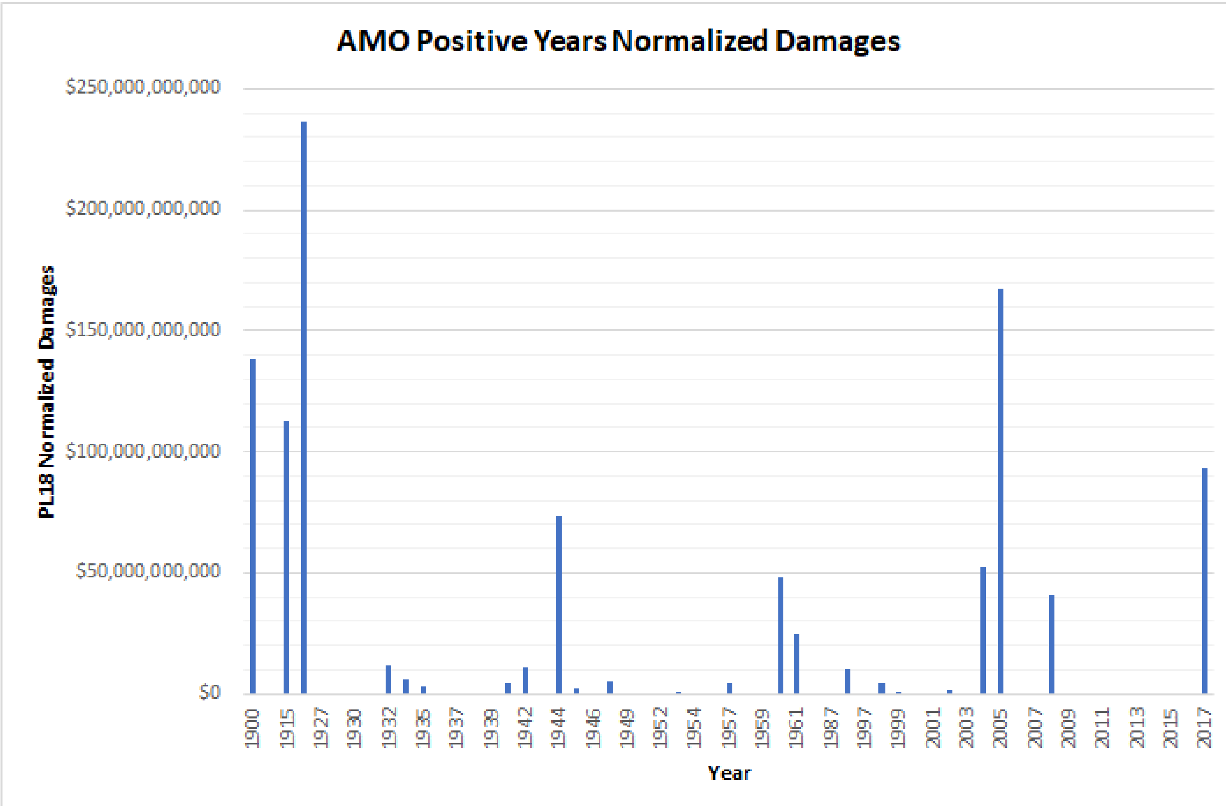

Figure 3.26 AMO Positive Phase Normalized Damages [Jan-Dec Anomalies]

PL18 normalized damages from hurricane landfalls during the positive years of the AMO [using January-December SST average anomalies].

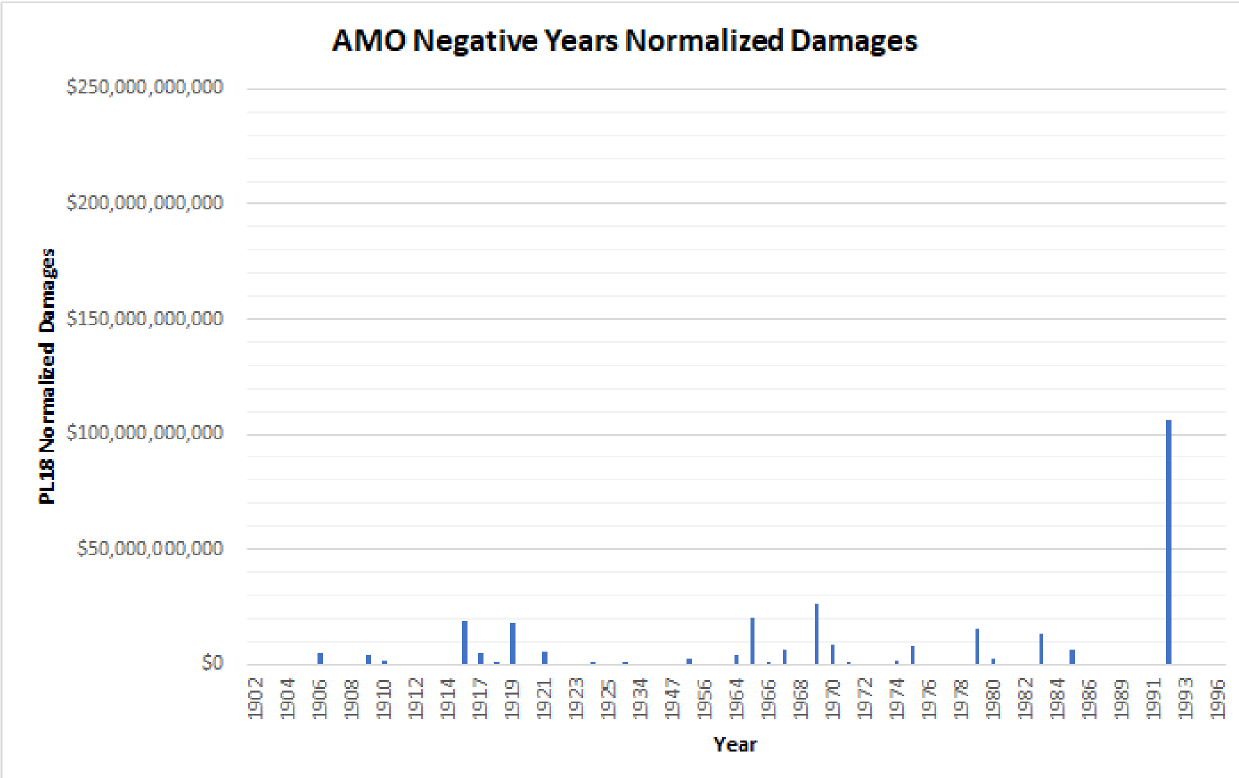

Figure 3.27 AMO Negative Phase Normalized Damages [Jan-Dec Anomalies]

PL18 normalized damages from hurricane landfalls during the negative years of the AMO [using January-December SST average anomalies].

The elimination of Category 1-2 landfalls to determine the damages from MHs during each phase, reveals that the positive phase MH damages was $1.005 trillion (Figure 3.28) and the negative phase MH damages was $273 billion (Figure 3.29).

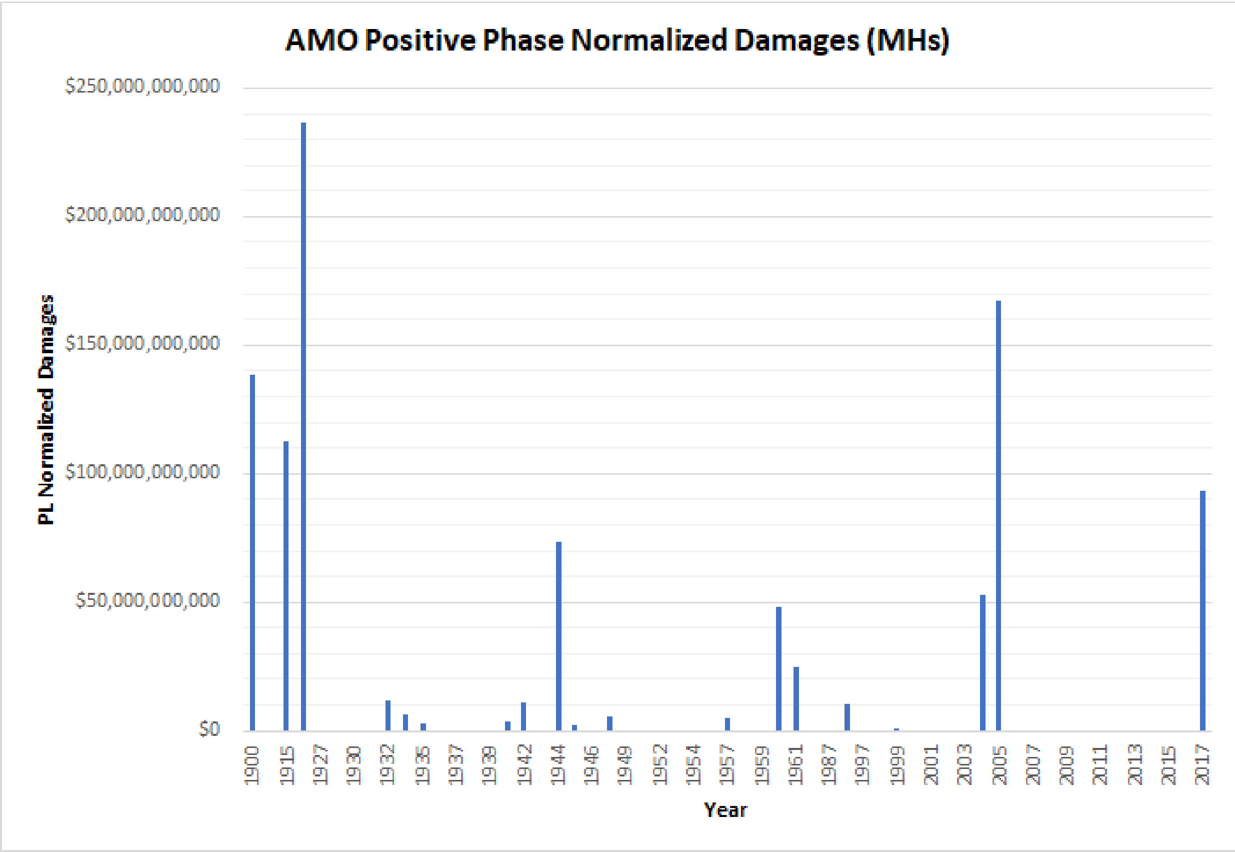

Figure 3.28 AMO Positive Phase Normalized Damages [Jan-Dec Anomalies] (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the positive years of the AMO [using January-December SST average anomalies].

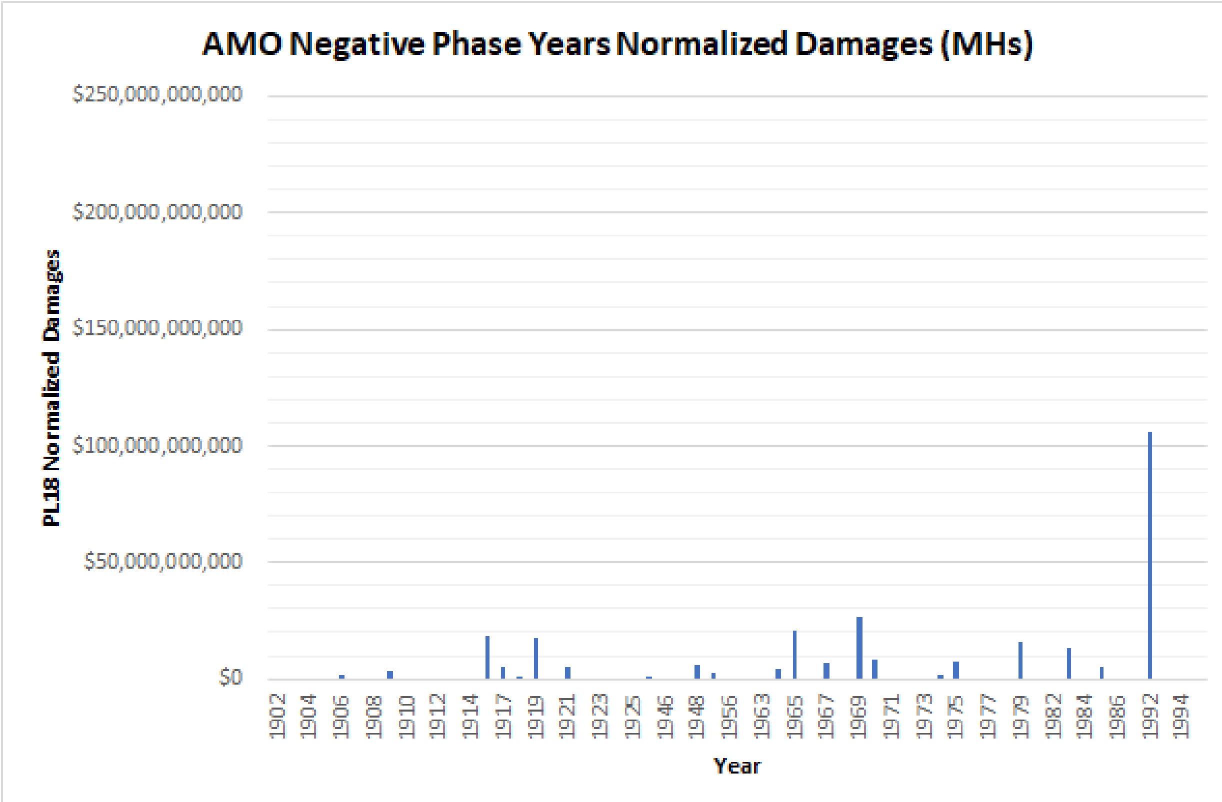

Figure 3.29 AMO Negative Phase Normalized Damages [Jan-Dec Anomalies] (Major Hurricanes)

PL18 normalized damages from major hurricane landfalls during the negative years of the AMO [using January-December average SST anomalies].

To determine a possible explanation as to why the cost of damages was so much higher during the positive phase, the number of landfalls exceeding $100 billion, representing the top costliest hurricanes, were considered for each phase. During the positive phase, there were 4 landfalls that exceeded $100 billion in damages, while during the negative phase there was only 1 landfall that exceeded $100 billion, which was still less than each of the 4 landfalls during the positive phase. Next, the years of the top costliest landfalls during the positive phase were compared to the average SST anomalies for the 5-month, June-October period, to see if the costliest landfalls corresponded to the highest SST anomalies. The inquiry did not show any relationship between the costliest hurricanes and the highest SST anomaly averages. This suggests that there were other circumstances that may have contributed to the extreme cost of hurricane landfalls during the positive phase of the AMO.

Discussion

The analysis of destructiveness to the Gulf Coast since 1900 has demonstrated the substantial economic strife the region has endured from hurricane landfalls. These findings are of great importance to stakeholders in order to adequately prepare for the anticipated landfalls during particular phases of each climate index and mitigating the fiscal hardships that follow. The data presented in this section upholds the expected results based on previous research of oceanic and atmospheric conditions during each teleconnection.

The findings reveal that there is an unambiguous relationship between destructiveness and the positive phase of the AMO. Damages during this phase since 1900 have exceeded $1 trillion from the 33 landfalls, making it the costliest climate index that was investigated in this study. While the number of landfalls hardly differed, the data revealed that there were three times as many $100 billion landfalls. The current findings further suggest that warmer SSTs are contributing to higher-strength hurricanes that may be causing such unprecedented damages. Other variables that may have influenced the cost of positive phase landfalls could include: strength of vertical wind shear, sea level pressure, strength in the circulation of the thermohaline in the North Atlantic, differences in the location of landfalls as well as the intensity of each landfall, as well as chance. While storm surge height and the density of homes and buildings can have a significant effect on the cost of damages that result from landfalling storms, these variables are independent of the AMO and do not provide an understanding of oceanic and atmospheric conditions during the positive phase. Thus, these storms should be analyzed individually to determine factors, other than SST, that influence the destructive potential during the positive phase of the AMO.

The next significant climate index examined was ENSO. Specifically, non-El Nino years (La Nina and neutral phases) collectively had approximately 4.5 times as many landfalls as El Nino years, and over $1 trillion in damages. Individually, the neutral phase had roughly 2.5 times the damage compared to the negative (La Nina) phase. Due to weaker upper and lower-level winds, reduced wind shear, and decreased atmospheric stability that results during La Nina, it was expected that there would have been more of an apparent number of landfalls and associated damages during the negative phase. The number of landfalls during La Nina did exceed that of the neutral phase, supporting the assumption. Still, damages during the neutral phase of ENSO exceeded $800 billion, making it the most impactful phase of the teleconnection. Stakeholders should be aware of the trend in landfall totals and cumulative damages during non-El Nino years.

The landfall totals and damage data from the positive and negative phase of the NAO was found to be inconclusive. However, when considering only the top 20 most positive and negative years, the data was more telling. The extreme negative phase years had almost five times as many landfalls, and approximately eight times the damage as the extreme positive phase years. With a total of $128 billion in damages during the extreme negative years, compared to $16.5 billion during the extreme positive years, it is reasonable to presume that strong negative years during the NAO should be of high concern to stakeholders along the Gulf Coast.

Overall, damages from hurricane landfalls along the Gulf Coast have cost over $1.3 trillion dollars, and the economic impacts from landfalls is increasing by tens of millions of dollars each year. The climate index data pertaining to damages should generate an urgent awareness to Gulf Coast residents, business owners and policy holders concerning the destructive potential from landfalling hurricanes. Additionally, this information should guide the essential mitigation practices to limit such calamitous losses in the future.

CHAPTER IV

DISCUSSION

The analysis of intensification in the Gulf of Mexico and associated destructiveness along the U.S. Gulf Coast has revealed the significance of natural climate oscillations on hurricane genesis, intensification, intensity, and devastation. Moreover, the study provides additional evidence with respect to increases in population growth and wealth related to increases in damages. The positive phase of the AMO showed the highest implication to intensification and destructiveness, given the unprecedented damages yielding over $1 trillion in damages, and a statistically significant relationship to SST and intensity. Additionally, the positive phase of the AMO showed the highest number of intensifying hurricanes along the coastline, emphasizing the exposure to intensified hurricanes the Gulf Coast has encountered.

The data from the statistical tests, intensification counts, and destructiveness analysis was found to be inconclusive for the NAO. A possible explanation for this might be that the NAO is predominantly an atmospheric mode (Barnston & Livezey, 1987) and thus, is marginally affected by SST (Lim, Y. K. et al., 2016) and affected to a greater degree by vertical wind shear. Due to the inconclusive results regarding the principal phase of the NAO on hurricane intensification and destructiveness, the 20 most extreme values for each phase were obtained and the analysis was conducted again. The results for the extreme years were more decisive. The number of intensifying storms was greater in the negative phase compared to the positive phase along the coast. Moreover, the elimination of non-extreme years revealed that only 10% of the positive phase landfalls were during an extreme, positive NAO, whereas, roughly 50% of the negative phase landfalls occurred during an extreme, negative NAO. Further, the extreme negative years generated over eight times the damages for the positive phase. These findings suggest that a strong, negative NAO has a greater effect on hurricane intensification in the Gulf of Mexico, although further research is needed to more closely examine the links between wind shear and intensification.

Finally, the analysis for ENSO revealed an explicit difference in the number of landfalls and associated damages between non-El Nino years and El Nino years. Non-El Nino years exceeded $1 trillion in damages and had over four times the number of landfalls as El Nino years. When considering the negative and neutral phase of ENSO individually, the neutral phase had over $800 billion in damages, while the negative phase had just over $300 billion. However, the negative phase had nine more landfalls than the neutral phase. This discrepancy could be attributed to the 4 years during the neutral phase that had damages exceeding $100 billion, whereas the negative phase did not have any years amounting $100 billion. These results are consistent with those of Elsner et al. (2000), wherein La Nina years experienced a greater number of U.S. landfalling hurricanes, and neutral years had the greatest number of catastrophic events (>$10 billion), and the highest 1997 normalized mean losses for the 73-year study period. The statistical tests for El Nino and non-El Nino years were found to be overtly different. The relationship between intensification, intensity and SST was found to be insignificant for the positive phase (El Nino years). However, the relationship between variables for the negative (La Nina years) and neutral phase were all found to be significant. Pointedly, intensity had the greatest effect on intensification during the negative phase, and SST had a greater effect on intensification during the neutral phase. The negative phase provided the largest set of significant clusters of intensification counts, however, they were not directly along the coastline where the focus was specified. Still, the trend of higher intensification counts moving from the Caribbean to the northwest though the basin should be noted. The neutral phase, on the other hand, had more clusters closer and adjacent to the coast with higher intensification counts. While the negative phase of ENSO is prone to a higher frequency of landfalls, the neutral phase should not be overlooked. The substantial damages during the neutral phase could be attributed to hurricanes that intensified as a result of high SST given the highly significant relationship between the two variables.

The findings of this study suggest that in general, non-El Nino years, the positive phase of the AMO, and a strong, negative NAO have the greatest influence on the number of Gulf Coast hurricane landfalls, intensification, and damages. Therefore, these teleconnections should be of highest regard to Gulf Coast stakeholders. However, the findings in this report are subject to limitations. First, the bi-monthly MEI values for August-October that were averaged for the purposes of classifying positive, negative, and neutral years of ENSO, used +/- 0.4° C as the decisive Nino 3.4 SST anomaly. However, NOAA uses Nino 3.4 SST anomalies up to +/- 0.5° C. The use of this greater value could change the classification years, and thus, alter the phase in which hurricanes made landfall. This could have implications on the statistical analyses, and destructiveness findings. Secondly, the examination of the effects of hurricane damages on wealth using state GDP was unavailable prior to the year 1963. The lack of data prior to 1963 eliminates 34 landfalls in the analysis causing the overall trend to be inconclusive. Finally, the analysis does not include all major and minor hurricanes within the study period. Only hurricanes that made landfall along the Gulf Coast and were a Category 3 or higher at some point along their tracks were included. Therefore, it cannot be emphatically concluded that increases in hurricane intensity and frequency are contributing to increases in damages. Additionally, it cannot be assumed that the geographic distribution of landfalls was contributing to the role in the losses. As seen in the map showing major hurricane tracks from 1900-2017, the landfalls included in this study are relatively evenly distributed across the U.S. Gulf Coast from Brownsville, TX to the Florida Keys.

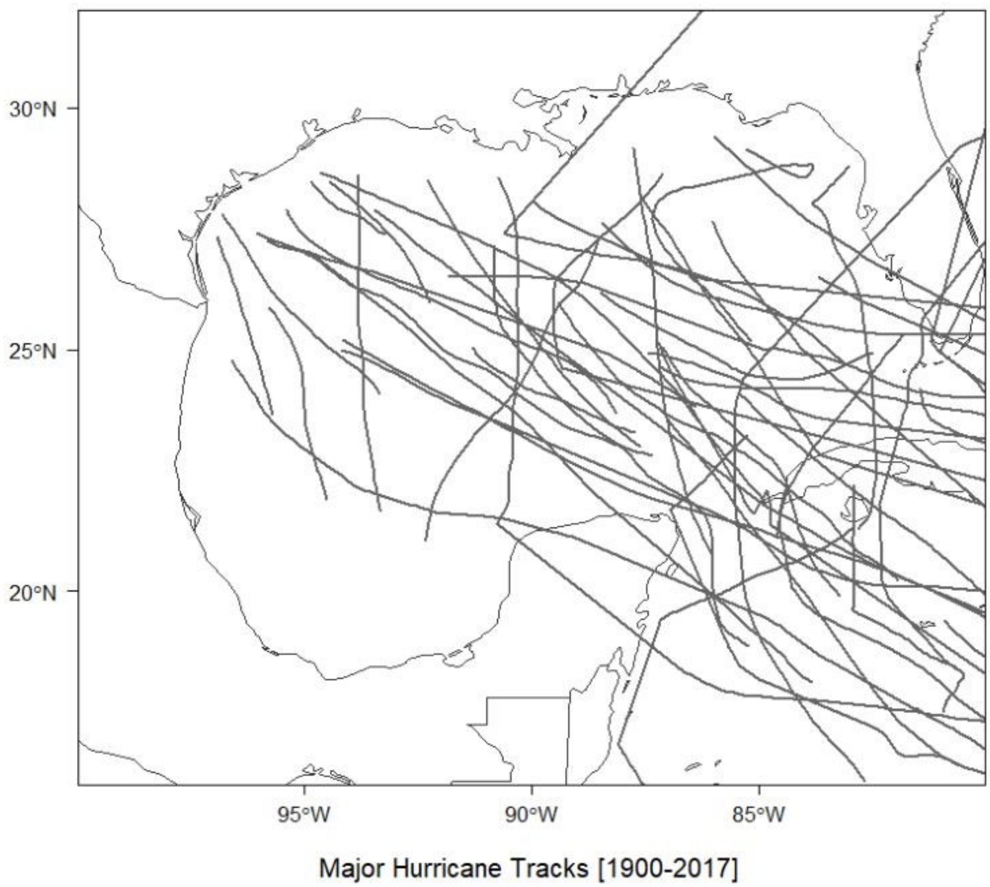

Figure 4.1 Major hurricane tracks in the Gulf of Mexico from 1900-2017.

Map of the Gulf of Mexico depicting the tracks of the 65 hurricanes included in the study that made landfall over the period 1900-2017.

This work contributes to existing knowledge of hurricane intensification by providing a comparative analysis of significance for three teleconnections that influence Gulf of Mexico TC activity. The present study provides additional evidence with respect to destructiveness along the U.S. Gulf Coast pertaining to each climate index. Additionally, the study confirms previous findings with regard to the influence of teleconnection patterns on hurricane formation, intensification and destructiveness. Finally, with the onset of global climate change, many studies have been more focused on recent trends in hurricane frequency, intensity, and destructiveness. The current research, however, covers a longer study period than most other studies, and provides a better overall trend of hurricane frequency, intensity, and destructiveness.

CHAPTER V

CONCLUSION

The main goal of the current study was to determine the effect of natural climate variability on the intensification of hurricanes in the Gulf of Mexico. Additionally, this study set out to determine the trend in destructiveness from landfalling hurricanes along the Gulf Coast. The results of this research showed that a positive AMO has contributed to the largest economic losses from landfalling storms amounting to \$1.050 trillion. This unprecedented value is largely due to four years in which damages exceeded \$100 billion each. Non-El Nino years (La Nina and neutral years) also showed substantial economic losses which exceeded \$1.056 trillion when taken together. Individually, neutral years of ENSO had the greatest economic losses, chiefly due to four years where landfalls exceeded \$100 billion each. The findings of the damages during the NAO were not substantially different between phases. During the positive phase, damages from landfalling hurricanes totaled approximately \$650 billion, while the damages during negative phase totaled nearly \$685 billion. Upon examining the top 20 positive and negative years, the results were more distinct. The damages during extreme positive years amounted to just \$6.5 billion, whereas the damages during extreme negative years amounted to nearly \$125 billion. The exceptional damages that have resulted over the last 118 years has demonstrated the consequential economic toll that hurricane landfalls have on Gulf Coast states. The growth in population and wealth along the Gulf Coast has certainly contributed to the overall trend in damages seen during the study period and is likely to continue to increase as people continue to sprawl to vulnerable coastal counties in this region of the United States.

The statistical findings in this research revealed that the positive phase of the AMO has the greatest influence on intensification in the Gulf of Mexico. Intensity and SST emerged as reliable predictors for hurricane intensification during the positive phase. During the ENSO climate index, non-El Nino years were shown to have a statistically significant relationship with hurricane intensification in the Gulf of Mexico. Specifically, the results suggest that intensity is playing the greatest role in intensification during the negative phase, whereas SST has the greatest effect on intensification during the neutral phase. The statistical findings for the NAO were inconclusive, initially, as intensity and SST were shown to have a statistically significant positive relationship with intensification during both phases. Upon examining the results for only the top 20 positive and negative years, the findings were more well-defined. The results indicated that the extreme positive years of the climate index did not have a statistically significant relationship with hurricane intensification. However, intensity was shown to have a highly significant relationship to intensification during extreme negative years. Whilst this study did not explicitly confirm that the negative phase of the NAO has a greater influence on hurricane frequency, intensity and destructiveness, it did partially substantiate that a strong, negative NAO contributes to these responses. Thus, the NAO should be studied more extensively with regard to other influential variables, such as wind shear.

Climate scientists should be aware of the long-term trend in the relationship between climatic modes of natural variability and hurricane intensification in the Gulf of Mexico. Rising SSTs due to climate change will likely result in higher intensities and increased numbers of intensifying storms throughout the North Atlantic. Thus, monitoring SSTs and intensities during the prominent phases of each climate index will play a crucial role in predicting the possibility of intensifying hurricanes making landfall along the Gulf Coast. While the substantial economic impacts from hurricane landfalls is a critical basis for the implementation of better mitigation practices, the social impacts that result from hurricane landfalls are paramount and should not be overlooked. Therefore, mitigation research and implementation should be at the forefront of policy in Gulf Coast states in an effort to limit the economic and social turmoil that result from landfalling hurricanes. Finally, the information presented in this study could guide government agencies to set aside funds for disaster-related costs during the years that are identified as greater risk for hurricane activity.

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APPENDIX A

SUPPLEMENTARY TABLES

Table A.1 Population and housing units during landfall year adjusted for inflation and population (Weinkle et al., 2018).

Total of Counties Affected by Storms								
Storm ID	Year	Storm Name	Original Population	2018 Population	Population Multiplier	Original Housing Units	2018 Housing Units	Housing Units Multiplier
1900_1	1900	Galveston	125,809	5,382,827	42.786	29,341	2,144,409	73.085
1906_6	1906		89,484	569,790	6.367	18,127	255,456	14.092
1906_8	1906		35,526	4,606,889	100.000	10,378	2,018,706	140.000
1909_4	1909	Velasco	70,742	730,213	10.322	17,081	308,555	18.064
1909_9	1909	Grand Isle	420,707	1,045,386	2.485	98,003	530,377	5.412
1909_11	1909		21,207	67,891	3.201	5,861	53,682	9.160
1910_5	1910		49,504	1,381,231	27.901	18,861	882,175	46.773
1915_2	1915	Galveston	221,149	5,382,827	24.340	54,763	2,144,409	39.158
1915_6	1915	New Orleans	451,042	1,045,386	2.318	108,944	530,377	4.868
1916_2	1916		169,380	995,969	5.880	35,368	483,738	13.677
1916_6	1916		27,788	394,374	14.192	6,091	168,443	27.655
1917_4	1917		70,321	471,825	6.710	17,515	257,732	14.715
1918_1	1918		4,019	4,317	1.074	814	2,199	2.702
1919_2	1919		19,751	67,891	3.437	5,813	53,682	9.234
1921_6	1921	Tampa Bay	154,507	3,256,579	21.077	47,023	1,618,915	34.428

Table A.1 (continued)

1924_10	1924		112,285	4,984,523	44.392	34,383	2,258,214	65.678
1926_3	1926		90,208	274,709	3.045	18,951	112,596	5.941
1926_7	1926	Great Miami	116,985	4,538,998	38.800	35,794	1,965,025	54.898
1929_2	1929		149,746	3,136,419	20.945	45,245	1,392,350	30.773
1932_2	1932	Freeport	23,857	370,285	15.521	5,994	140,502	23.442
1933_8	1933		91,258	487,208	5.339	19,822	167,225	8.436
1935_3	1935	Labor Day	13,851	67,891	4.902	4,551	53,682	11.796
1941_2	1941		697,877	5,418,525	7.764	195,268	2,163,362	11.079
1941_5	1941		295,714	3,068,528	10.377	93,576	1,338,668	14.306
1942_3	1942		732,495	5,114,744	6.983	208,683	2,062,965	9.886
1944_13	1944		74,501	1,727,844	23.192	31,334	1,054,495	33.653
1945_5	1945		183,098	477,104	2.606	50,566	216,753	4.287
1948_8	1948		32,992	445,525	13.504	12,936	293,189	22.664
1950_Easy	1950	Easy	43,970	972,640	22.121	18,501	488,671	26.413
1953_Florence	1953	Florence	50,022	185,360	3.706	16,899	116,622	6.901
1957_Audrey	1957	Audrey	61,130	83,651	1.368	18,476	37,937	2.053
1960_Donna	1960	Donna	63,674	445,525	6.997	27,373	293,189	10.711
1960_Donna_9	1960	Donna_9	1,013,537	2,481,238	2.448	319,668	1,124,105	3.516

Table A.1 (continued)

1960_Ethel	1960	Ethel	175,011	331,375	1.893	50,310	156,395	3.109
1961_Carla	1961	Carla	154,048	472,487	3.067	52,409	199,561	3.808
1964_Hilda	1964	Hilda	120,483	173,316	1.439	32,575	71,185	2.185
1964_Isabel	1964	Isabel	372,193	2,078,807	5.585	152,741	1,132,575	7.415
1965_Betsy	1965	Betsy	50,254	67,891	1.351	19,454	53,682	2.759
1965_Betsy_9	1965	Betsy_9	1,011,398	777,668	0.769	322,720	418,954	1.298
1966_Alma	1966	Alma	35,293	90,518	2.565	13,359	44,848	3.357
1966_Inez	1966	Inez	50,720	67,891	1.339	19,709	53,682	2.724
1967_Beulah	1967	Beulah	426,236	881,164	2.067	128,383	335,474	2.613
1969_Camille	1969	Camille	175,082	249,877	1.427	54,738	120,959	2.210
1970_Celia	1970	Celia	303,228	455,136	1.501	97,632	204,405	2.094
1971_Edith	1971	Edith	109,950	138,889	1.263	34,644	60,834	1.756
1974_Carmen	1974	Carmen	205,478	246,535	1.200	62,298	102,366	1.643
1975_Eloise	1975	Eloise	204,259	441,038	2.159	78,894	278,051	3.524
1979_Frederic	1979	Frederic	551,862	785,535	1.423	201,946	383,337	1.898
1980_Allen	1980	Allen	227,222	486,790	2.142	71,314	167,030	2.342
1983_Alicia	1983	Alicia	397,604	736,863	1.853	160,051	305,257	1.907
1985_Elena	1985	Elena	697,499	829,427	1.189	273,823	387,685	1.416

Table A.1 (continued)

1985_Kate	1985	Kate	131,762	215,190	1.633	65,184	136,780	2.098
1992_Andrew	1992	Andrew	2,000,348	2,690,893	1.345	787,486	1,099,161	1.396
1992_Andrew_9	1992	Andrew_9	224,946	246,535	1.096	84,102	102,366	1.217
1995_Opal	1995	Opal	290,993	433,953	1.491	135,462	238,702	1.762
1998_Georges	1998	Georges	79,276	67,891	0.856	50,537	53,682	1.062
1998_Georges_9	1998	Georges_9	749,267	799,597	1.067	310,217	367,527	1.185
1999_Bret	1999	Bret	419	418	0.998	274	195	0.710
2002_Lili	2002	Lili	378,354	436,580	1.154	154,385	188,849	1.223
2004_Charley	2004	Charley	3,067,686	4,010,677	1.307	1,443,451	2,009,490	1.392
2004_Ivan	2004	Ivan	501,369	621,324	1.239	242,210	325,052	1.342
2005_Dennis	2005	Dennis	591,912	694,206	1.173	276,788	351,502	1.270
2005_Katrina	2005	Katrina	5,661,182	5,943,686	1.050	2,419,980	2,687,809	1.111
2005_Rita	2005	Rita	343,979	336,102	0.977	142,764	144,236	1.010
2005_Wilma	2005	Wilma	5,823,087	6,659,289	1.144	2,615,421	3,113,980	1.191
2008_Gustav	2008	Gustav	311,302	329,730	1.059	125,324	135,894	1.084
2008_Ike	2008	Ike	4,270,445	5,012,542	1.174	1,679,625	2,003,907	1.193
2017_Harvey	2017	Harvey	4,692,533	4,761,583	1.015	1,869,883	1,900,479	1.016
2017_Irma	2017	Irma	5,725,798	5,787,054	1.011	2,707,411	2,746,248	1.014

Table A.2 PL18 normalized damages of Gulf Coast hurricane landfalls during the period 1900-2017. Gray-shaded rows indicate landfalls that were not a major hurricane at landfall (Category 1 or 2). Dataset includes storm name/ID, year of landfall, category at landfall, state(s) affected, base economic damages, normalized damages and damages as a percent of state GDP. (Weinkle et al., 2018)

Year	Storm ID	Storm Name	Category	State	Base Economic Damage (US $)	Normalized PL 2018
1900	1900_1	Galveston	4	TX	$30,000,000	$138,614,443,808
1906	1906_6		2	MS,AL,FL,LA	$4,000,000	$2,617,105,234
1906	1906_8		3	FL	$200,000	$2,055,050,860
1909	1909_11		3	FL	$1,000,000	$317,023,768
1909	1909_4	Velasco	3	TX	$2,000,000	$2,044,406,587
1909	1909_9	Grand Isle	3	LA,MS	$5,000,000	$1,230,362,596
1910	1910_5		2	FL	$500,000	$1,363,773,213
1915	1915_2	Galveston	4	TX,LA	$50,000,000	$109,804,069,871
1915	1915_6	New Orleans	3	LA,MS	$13,000,000	$2,718,479,452
1916	1916_2		3	MS,AL,FL	$31,000,000	$16,174,854,664
1916	1916_6		4	TX	$1,800,000	$2,266,815,245
1917	1917_4		3	FL,LA,AL		$4,768,639,699
1918	1918_1		3	LA,TX	$5,000,000	$460,735,896
1919	1919_2		4	FL,TX	$22,000,000	$17,841,684,788
1921	1921_6	Tampa Bay	3	FL	$3,000,000	$5,165,126,129
1924	1924_10		1	FL,FL		$773,845,744
1926	1926_3		3	LA	$4,000,000	$918,924,236

Table A.2 (continued)

1926	1926_7	Great Miami	4	AL,MS,FL	$105,000,000	$235,948,025,762
1929	1929_2		3	FL	$300,000	$459,285,224
1932	1932_2	Freeport	4	TX	$7,500,000	$11,525,438,487
1933	1933_8		3	TX	$12,000,000	$6,040,334,556
1935	1935_3	Labor Day	5	FL, GA	$6,000,000	$2,712,332,116
1941	1941_2		3	TX	$7,000,000	$3,566,919,234
1941	1941_5		2	FL, GA	1,000,000	681,005,840
1942	1942_3		3	TX	$26,500,000	$10,790,348,722
1944	1944_13		3	FL	$63,000,000	$73,466,498,945
1945	1945_5		3	TX	$20,000,000	$2,461,282,998
1948	1948_8		4	FL	$12,000,000	$5,515,401,644
1950	1950_Easy	Easy	3	FL	$3,300,000	$2,246,898,463
1953	1953_Florence	Florence	1	FL	$200,000	$19,871,992
1957	1957_Audrey	Audrey	3	LA,TX	$150,000,000	$4,547,098,823
1960	1960_Donna	Donna	4	FL,NC,VA,NY, CT, RI, MA	$387,000,000	$48,392,370,612
1960	1960_Ethel	Ethel	1	LA,MS	$1,000,000	$39,630,416
1961	1961_Carla	Carla	4	TX	$400,000,000	$25,095,759,124
1964	1964_Hilda	Hilda	3	LA	$125,000,000	$3,308,030,460
1964	1964_Isabel	Isabel (Isbell)	3	FL	$10,000,000	$1,027,526,533
1965	1965_Betsy	Betsy	3	FL,LA	$1,420,000,000	$20,513,468,517
1966	1966_Alma	Alma	2	FL	$10,000,000	$417,692,725
1966	1966_Inez	Inez	1	FL	$5,000,000	$108,995,318

Table A.2 (continued)

1967	1967_Beulah	Beulah	3	TX	$200,000,000	$6,317,866,988
1969	1969_Camille	Camille	5	LA, MS	$1,421,000,000	$26,414,019,804
1970	1970_Celia	Celia	3	TX	$454,000,000	$8,252,290,737
1971	1971_Edith	Edith	2	LA	$25,000,000	$352,244,329
1974	1974_Carmen	Carmen	3	LA	$150,000,000	$1,410,764,694
1975	1975_Eloise	Eloise	3	FL, AL	$490,000,000	$7,747,515,932
1979	1979_Frederic	Frederic	3	AL,MS	$2,300,000,000	$15,827,205,699
1980	1980_Allen	Allen	3	TX	$300,000,000	$2,766,227,873
1983	1983_Alicia	Alicia	3	TX	$2,000,000,000	$13,640,282,313
1985	1985_Elena	Elena	3	AL,MS,FL	$1,250,000,000	$4,990,180,575
1985	1985_Kate	Kate	2	FL,GA	$300,000,000	$1,644,846,703
1992	1992_Andrew	Andrew	5	FL,LA	$31,500,000,000	$106,040,315,676
1995	1995_Opal	Opal	3	FL,AL	$3,000,000,000	$10,048,811,036
1998	1998_Georges	Georges	2	FL,MS	$2,310,000,000	$4,546,500,713
1999	1999_Bret	Bret	3	TX	$60,000,000	$114,507,945
2002	2002_Lili	Lili	1	LA	$860,000,000	$1,657,826,975
2004	2004_Charley	Charley	4	FL,SC	$14,000,000,000	$26,932,343,549
2004	2004_Ivan	Ivan	3	AL,FL	$14,200,000,000	$25,893,348,510
2005	2005_Dennis	Dennis	3	FL,AL	$2,230,000,000	$3,542,320,160
2005	2005_Katrina	Katrina	3	FL,LA,MS,AL	$82,200,000,000	$116,888,574,230
2005	2005_Rita	Rita	3	LA,TX	$11,254,000,000	$14,893,539,790
2005	2005_Wilma	Wilma	3	FL	$20,600,000,000	$31,907,535,239
2008	2008_Gustav	Gustav	2	LA	$4,300,000,000	$5,456,056,462
2008	2008_Ike	Ike	2	TX,LA	$25,000,000,000	$35,152,707,968

Table A.2 (continued)

2017	2017_Harvey	Harvey	4	TX	$60,000,000,000	$62,191,097,565
2017	2017_Irma	Irma	4	FL	$30,000,000,000	$30,972,463,481