EFFECTS OF ENSO ON ATLANTIC HURRICANE FORMATION

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Effects of ENSO on Atlantic Hurricane Formation. (May 2015)

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Hurricanes in the Atlantic can have devastating impacts on United States coastal populations and infrastructure. Further researching hurricane movements and tendencies in synoptic climatic events, like the El Niño Southern Oscillation (ENSO), could benefit the safety of thousands of people every year as well as save millions of dollars. This paper analyzes the effects of ENSO on the length of time between tropical storm formation and landfall in the United States, as well as the number of landfalls per state per year. Almost 1,000,000 synthetic tropical cyclones were analyzed using a statistical stochastic program, which was programmed to return the time and coordinates between tropical storm formation and landfall. The time and distance for each hurricane during its respective episode of ENSO was averaged to get an idea of the time between formation and landfall during all 7 ENSO phases. Generally, the time between formation and landfall was found to be approximately 5 days regardless of ENSO intensity. La Niña has the longest distance between formation and landfall; however in comparison to the smallest distance (Strong El Niño) it is only a difference of about 300 km. This research combines our current understanding of the effects that ENSO has on Atlantic hurricanes with historically based synthetic data in order to potentially enhance warning preparations.

DEDICATION

I would like to dedicate this research paper to my amazing mom. Through all of the struggles and trials God has put us through, you not only provided for our family by working countless hours; you encouraged me and pushed me to be the best student I could be. Your never ending love and support has carried me through all of the times I doubted myself. I know I can rely on you to make a bad situation better, and to always look on the bright side of things. Thank you for being my comedian, rock, and most of all, my best friend. Sometimes we butt heads, but it is only because you always have my best interest at heart. I never take all of your hard work for granted! You are the reason I was able to write this paper. I hope you enjoy it and learn something exciting about weather and climatology.

ACKNOWLEDGEMENTS

I would like to thank my research advisor, Dr. John Nielsen-Gammon, for his outstanding support with my research. You have shown me so many possibilities with climatology, and I have grown significantly as a student and as a person through your continued support. Thank you for your patience with this learning experience, and for always having my best interest at heart.

I would also like to thank Dr. Timothy Hall for allowing me to use his programming code to complete this project. It was a tremendous help, and without your consent the results this project had would not have been the same!

CHAPTER I

INTRODUCTION

Hurricanes are highly dangerous when unprepared for. They are weather's own weapon of mass destruction; they can leave thousands homeless, injured, or even dead. 50% of the US population resides in coastal areas; over the past 40 years, these areas have grown to approximately 50 million residents, which is an increase of roughly 46%. By 2015, scientists expect the population in these regions to increase by an additional 7.1 million (Kim et al. 2014). Climate change is not only causing more extreme weather phenomena, like hurricanes, rainfall, river discharges and rising sea levels (Kim et al. 2014), but it is also causing subsidence along coastal regions. These sinking coastal areas, combined with increased populations and weather extremes, will lead to potentially hazardous outcomes (Mousavi et al. 2011).

Disaster planning for these events is crucial. If the time between hurricane formation and landfall is better understood, in any environmental condition, then the Emergency Management System can improve their hurricane season preparations and better tailor them to the actual hazards in a given season. Hurricanes are not affected by the Atlantic region alone but also by synoptic events, and better understanding these events and their effects on hurricanes can potentially save thousands if not millions of lives. One of these scenarios is during an El Niño Southern Oscillation (ENSO) phase shift, whether it be El Niño or La Niña. Previous analyses have shown that an ENSO warm [cold] phase decreases [increases] hurricane activity in the North Atlantic region on a general scale (Smith et al. 2007). Based on climatological records provided by the

U.S. National Hurricane Center, ENSO cold phase (La Niña) landfall frequencies are slightly larger than neutral-phase landfall frequencies (Smith et al. 2007).

The effects on public safety as well as my own previous research on the subject have inspired me to look into this topic more deeply. In 2014 another student and I completed research hypothesizing that El Niño (La Niña) decreases (increases) Atlantic hurricanes. Our results showed that an El Niño causes Atlantic hurricanes to curve back out to sea, while a La Niña causes Atlantic hurricanes to curve back towards the East and Gulf Coast (Collins and Tomasco 2014). After completing this research, another question was brought to my attention – does ENSO not only affect Atlantic tropical cyclone (TC) tracking, but other TC factors such as formation, propagation, and time to landfall? Longer time periods (1900-2009) have been used to examine the effect of ENSO on Atlantic TCs, and have found the same result: El Niño's have a negative correlation with Atlantic TC formation because of climate parameters like vertical wind shear which suppresses it (Klotzbach 2010). ENSO was examined as opposed to other synoptic climatological features like the MJO (Madden-Julian Oscillation), NAO (North Atlantic Oscillation) or AMM (Atlantic Meridional Mode) because ENSO shows the strongest effects on deep tropical activity (Kossin et al. 2010), which better satisfies the purposes of this paper.

A statistical methodology has been developed to use historical sea surface temperature and relative sea surface temperature to generate simulated hurricanes (Hall 2014); their intensification and development are according to climatological data during 1984-2010. These thousands of simulated hurricanes will allow for a more robust statistical analysis than historical hurricanes alone.

With Dr. Hall's permission, I used this simulated hurricane data set to examine the effect of ENSO episodes. In summary, the purpose of this paper is to explore and find how ENSO phase shifts affect different factors of an Atlantic TC. More specifically, the paper analyzes how ENSO effects the time between propagation and landfall of an Atlantic TC, as well as how we can use this information to improve the Emergency Management System's preparations during hurricane season.

CHAPTER II

METHODS

Dr. Timothy Hall has given my advisor and me the rights to use his dataset/methodology in order to create my own database. Hall and Yonekura (2013) describe this statistical stochastic model and utilize it to examine the life cycles of Atlantic TC's. The model uses historical TC's between 1950-2012 to create a database of potential hurricanes (i.e. a set of "imaginary" hurricanes) which total a little under 1,000,000. In doing so, the ENSO state was held neutral while looking at the effects of local sea surface temperatures (SST) compared to overall tropical SST. For the purposes of this paper, I used this same method with the difference of examining the different episodes of ENSO instead of holding that parameter neutral. This model outputs the number of state crossings for each coastal state, as well as the number of hurricanes that fall into each Saffir-Simpson Hurricane Scale category for that state (0-5). The coastal states used border the Gulf of Mexico and the Atlantic Ocean, extending from Texas to Maine.

Data Collection

Each simulation file is a text file that has hundreds of synthetic TC's in them. Each file has the following information:

1. The number of storms in the file, N.
2. N time series of 6-hourly data.
3. A header above each time series showing the year, storm count, and the number of 6-hourly time steps in the series.

4. M rows per storm that contain: step count, float day of year, longitude (in degrees E) and latitude (in degrees N) of storm center, maximum sustained winds denoted Vmax (one minute sustained winds at 10 meters altitude in km/hr, as defined by HURDAT), radius to Vmax (km), and a land-ocean flag (1 means the hurricane has hit land, 0 means it has not).

It is necessary to understand how the simulation files are constructed in order to understand how the programming code processes them. First, the Vmax thresholds define the Saffir-Simpson intensity categories. There are 6 categories (Category 0-5) whose Vmax minimum thresholds are defined below. Hall and Yonekura defined "cat 0" to be a TC between 0 and 118 km/hr in their model; a category 0 TC is later changed in this study to fall between 63-118 km/hr so as to exclude anything weaker than a tropical storm. However for the purposes of the statistical model, they were defined as the following, in units of km/hr:

- cat0 = 0.0
- cat1 = 119.0
- cat2 = 154.0
- cat3 = 178.0
- cat4 = 210.0
- cat5 = 249.0

The code then uses a previously written point-polygon routine (found online by Hall) to determine if a point is inside of a polygon. Each of the 20 coastal states was given a "shape file" (irregular polygon end points). These shape files are developed using a single point of longitude and latitude along the state's border; each shape has a vast amount of "points" which creates the shape we desire. Now that these 20 states "shapes" are open, each simulation file can be opened. The program opens each individual simulation file and looks at a few things. The location of the hurricane is tracked based on its longitude and latitude, and is determined to be a "state crossing" when its coordinates have crossed into a state shape. However, 6-hour time intervals are extremely inaccurate for hurricane tracking because storms may move very quickly. Storm locations are therefore linearly interpolated to an hourly time resolution so that the model outputs may be more precise. The code uses this information to see, state by state, if the interpolated hourly track points were over a state anywhere. If it was, the Vmax value from the 6-hour position prior to the state entry is used to determine the intensity of the storm.

Modifying for ENSO

In order to manipulate this code to output state crossings during ENSO phases, a list of years was compiled for each of the following cases: Strong El Niño, Strong La Niña, Moderate El Niño, Moderate La Niña, Weak El Niño, Weak La Niña, and Neutral. The MEI (Multivariate ENSO Index) developed by NOAA was used to determine the years in each of the seven categories. This was done by looking at the months in the year when ENSO has the strongest effect on Atlantic hurricanes; July, August, September and October (JASO) were therefore used in this study. The MEI JASO values were averaged and then "ranked" based on a percentile. The list of years in each ENSO category was determined using this percentile method – the top 10% was a strong La Niña, the next 10% was a moderate La Niña, and so on. In other words, a rank of "1" indicates a strong La Niña and a rank of "63" indicates a strong El Niño. The percentiles determined the rankings in this fashion:

- 1-6 Strong La Niña

- 7-12 Moderate La Niña
- 13-19 Weak La Niña
- 20-44 Neutral
- 45-51 Weak El Niño
- 52-57 Moderate El Niño
- 58-63 Strong El Niño

Table 1 below lists the resulting years pre-determined with the percentile/ranking system.

TABLE 1 – ENSO Years Categorized by Intensity and Phase

Strong El Niño	Moderate El Niño	Weak El Niño	Neutral		Weak La Niña	Moderate La Niña	Strong La Niña
1957	1951	1958	1952	1984	1962	1954	1950
1965	1969	1963	1953	1985	1967	1956	1955
1972	1976	1983	1959	1990	1974	1964	1973
1982	1992	1986	1960	1991	1989	1970	1975
1987	1993	2002	1961	1995	1998	1971	1988
1997	1994	2009	1966	1996	2007	1999	2010
			1968	2000	2011		
			1977	2001			
			1978	2003			
			1979	2004			
			1980	2005			
			1981	2008			
				2012			

To pull out the information desired for one phase, say a Strong El Niño, the program had a function that simply asks "Does the year from the simulation file match any of the years in this list?" and if so, the program would proceed. The program was run for each of the seven ENSO categories, which took about 25 hours per category and produced successful results.

In lieu of the crossing accumulations, the storm ID, year, formation coordinates and day/time, landfall coordinates and day/time, Vmax (i.e. intensity), and state that the storm made landfall were produced for each storm in those specified years. The code would output the data in a text file, which was then imported into Excel for further analysis. I used the formation coordinates and the landfall coordinates to calculate the distance between formation and landfall. This is under the assumption that the hurricane took a linear path. Each coordinate was converted to radians, and the Great Circle Equation was used to compute the distance between formation and landfall of the hurricane so that the curvature of the Earth would not be neglected. These distances were converted to kilometers and averaged. The time between formation and landfall was found by subtracting the formation day/time from the landfall day/time. The "time to landfall" was then also averaged over the entire storm set for each category.

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CHAPTER III

RESULTS

State Crossings for Each ENSO Phase

The number of landfalls per year was graphed by hurricane intensity (Category 0-5) as well as the state in which the hurricane made landfall. These results are shown below in Figures 1-7. It should be noted that a "Category 0 hurricane" is not a technical Saffir-Simpson category, but for the purposes of this paper is the equivalent of a tropical storm.

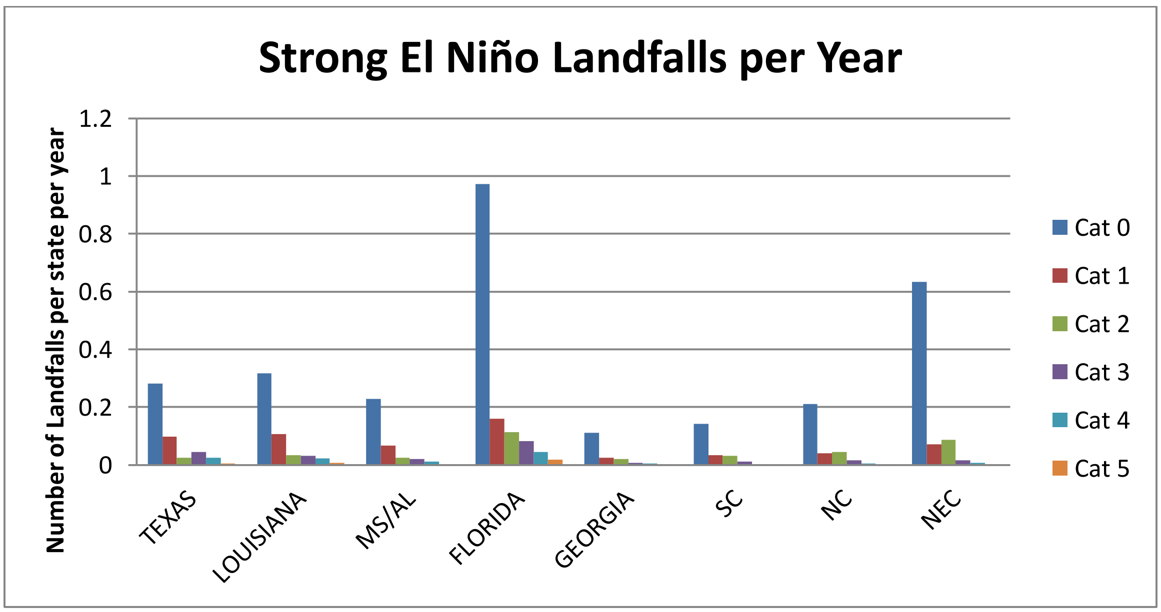

FIGURE 1 – The number of landfalls per state per year during Strong El Niño conditions, 1950-2012.

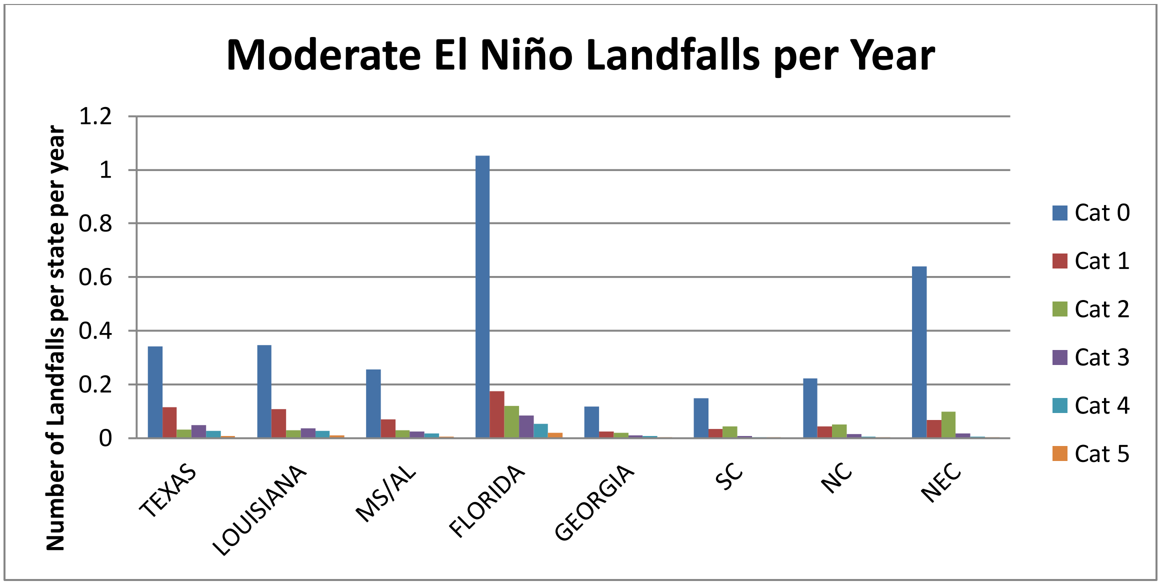

FIGURE 2 – The number of landfalls per state per year during Moderate El Niño conditions, 1950-2012.

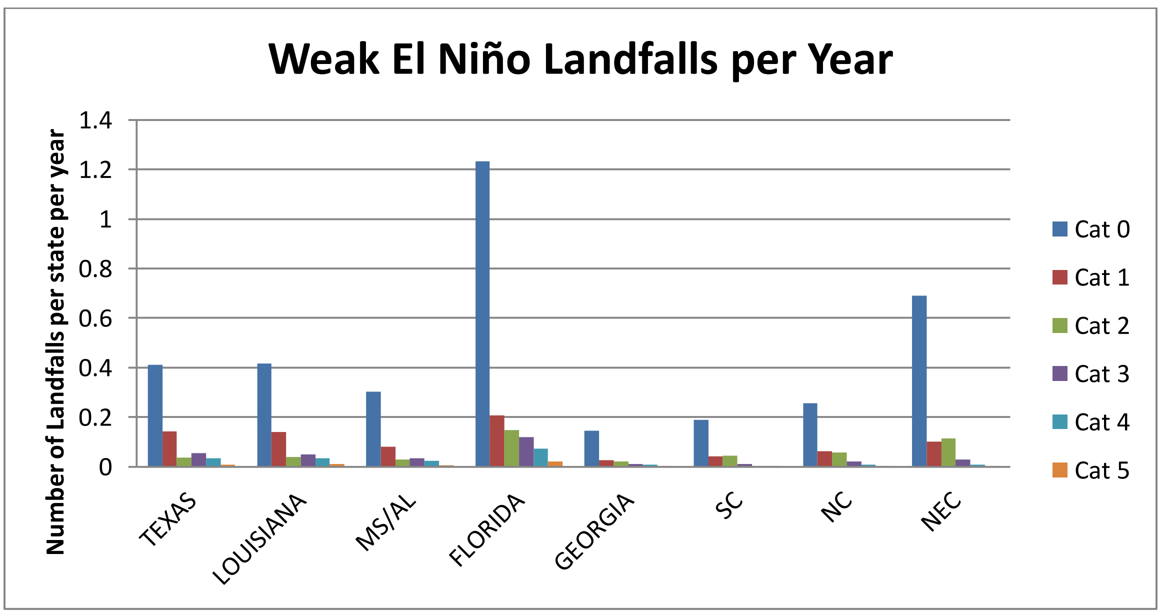

FIGURE 3 – The number of landfalls per state per year during Weak El Niño conditions, 1950-2012.

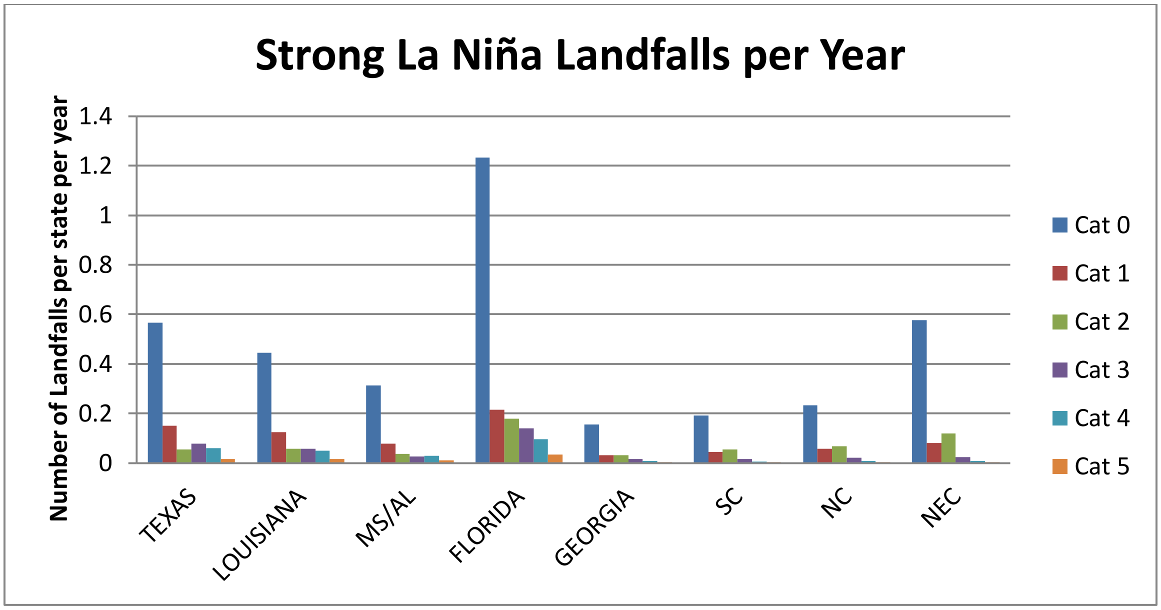

FIGURE 4 – The number of landfalls per state per year during Strong La Niña conditions, 1950-2012.

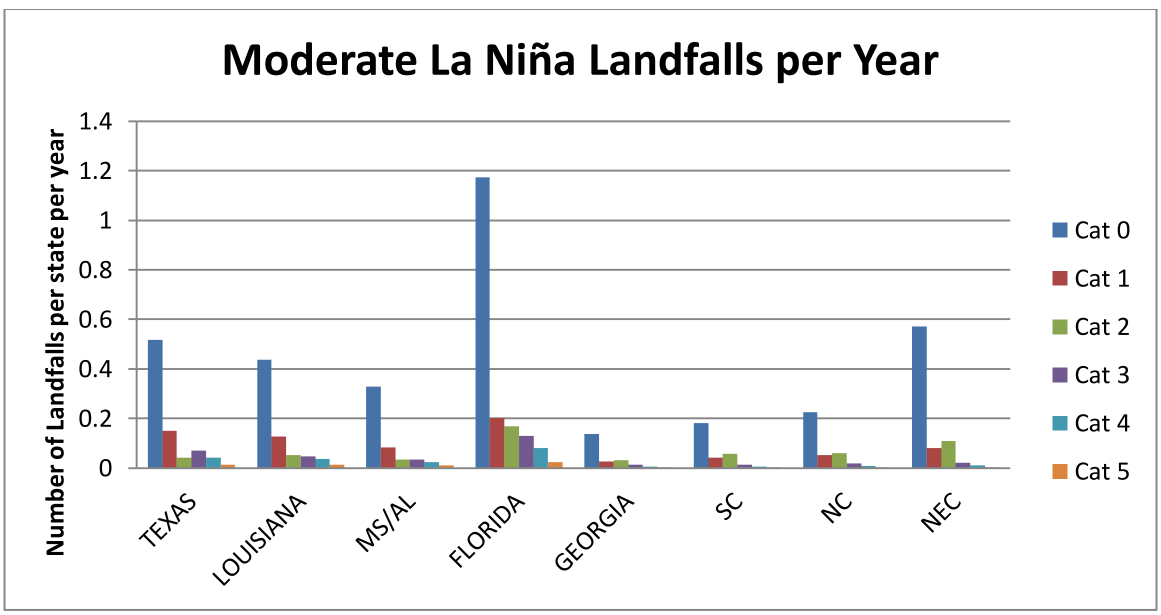

FIGURE 5 – The number of landfalls per state per year during Moderate La Niña conditions, 1950-2012.

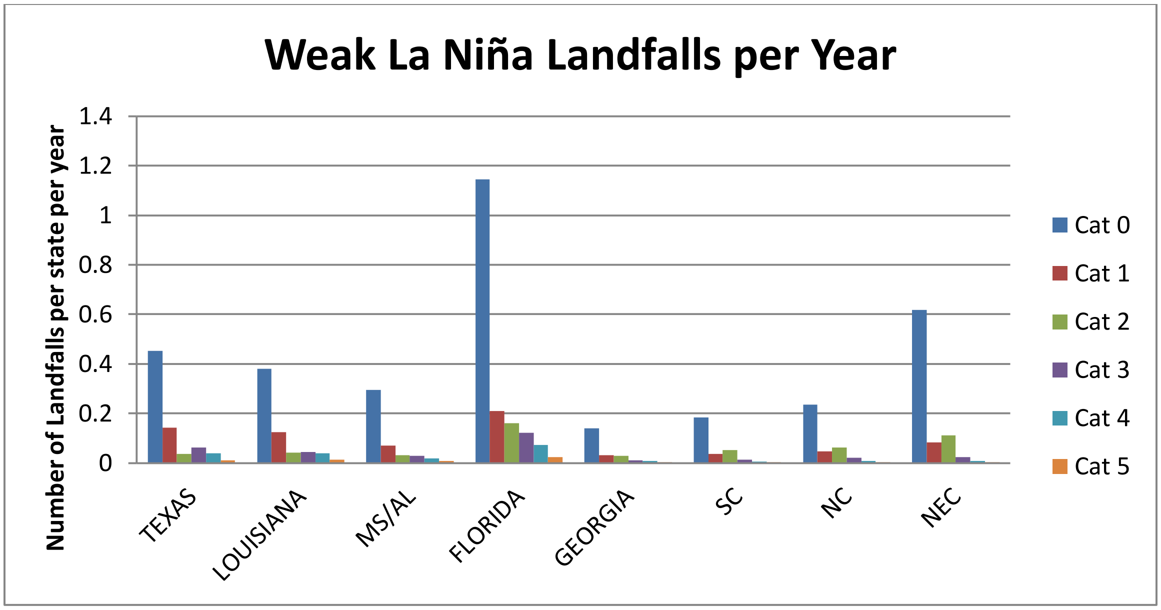

FIGURE 6 – The number of landfalls per state per year during Weak La Niña conditions, 1950-2012.

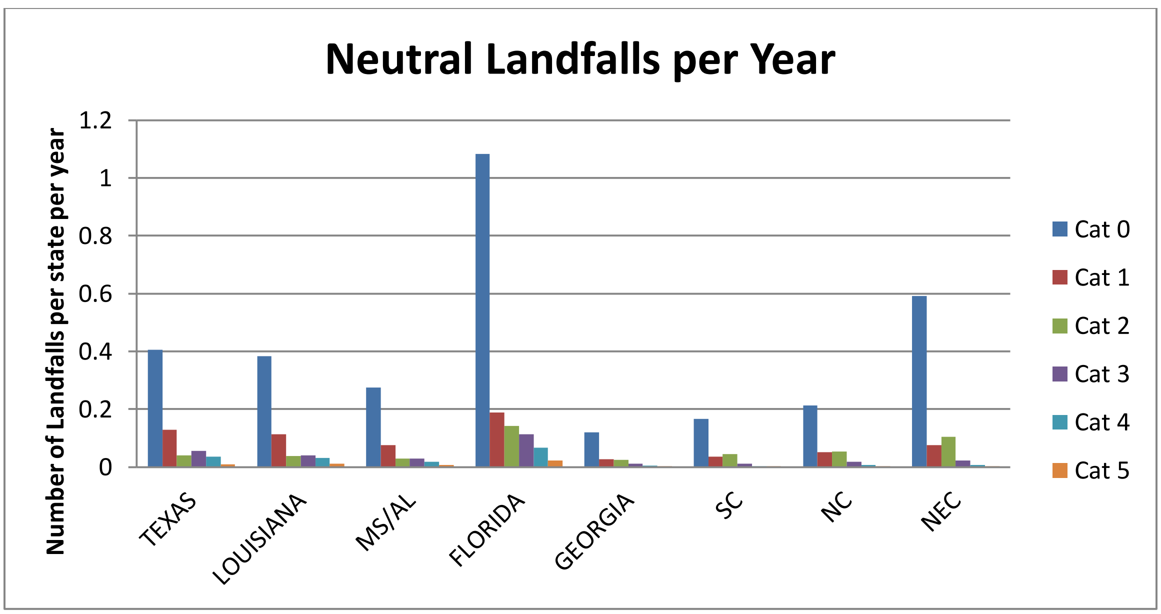

FIGURE 7 – The number of landfalls per state per year during Neutral conditions, 1950-2012.

A strong La Niña episode has a slightly stronger hurricane count in places like Texas and especially Florida, but this margin is rather slim. During a neutral phase, there is a significantly larger storm count is almost every coastal state. This can be due to the neutrality of the ENSO phase, as well as the larger year set. Basically, the stronger an El Niño phase gets, the fewer hurricanes there are that make landfall. This "strength" in phase is not a massive contributor to the total accumulation per state though. For example, when looking at Moderate El Niño vs. Strong El Niño, you can see visibly see the decrease in category 0 hurricanes per year in Florida. But the number of Texas and Louisiana category 0-2 hurricanes remains almost in the same position throughout moderate and strong El Niño. On the grand scale, La Niña has a larger storm landfall rate per year than El Niño does.

Effects of ENSO on Time to Landfall

For each ENSO phase and intensity, the average distance between formation and landfall as well as the average time between the two was calculated. This average was taken over a range between 13,000 to 138,000 synthetic storms, dependent upon the year classification for that phase. The number of landfalls per year was calculated by dividing the total number of landfalls (per category) first by the number of simulations, then by the number of years in the respective category. The results are as follows:

TABLE 2 – Average Distance, Time to Landfall and Landfalls per year by ENSO phase/intensity

	Average Distance (km)	Average Time to Landfall (days)	Landfalls per Year
Strong El Niño	1787.73	5.23	4.27
Moderate El Niño	1837.44	5.29	4.62
Weak El Niño	1853.07	5.27	5.51
Neutral	1924.98	5.41	4.95
Weak La Niña	1979.17	5.45	5.31
Moderate La Niña	1981.44	5.39	5.52
Strong La Niña	2083.91	5.63	5.83
ALL YEARS	**1928.55**	**5.40**	**5.09**

As you can see, the result is that the phase and strength of ENSO does not have a significant impact on the time to landfall. There are miniscule differences, but these differences are in terms of hours. A strong La Niña may have a longer time between formation and landfall, but this in on the order of a fraction of a day. In terms of average distance between formation and landfall, strong La Niña has the longest distance. In comparison to the smallest value, a strong La Niña has about a 296 km greater length. On the order of thousands of kilometers, this number is small, but can easily mean the difference between a hurricane making landfall or a recurving storm track.

Generally, an El Niño phase has fewer landfalls per year than a La Niña phase does. Specifically, you can see that a strong El Niño vs. a strong La Niña is about a 1.5 difference in the number of hurricanes. This validates with other results from this study. The "ALL YEARS" row is displayed to show the results from this synthetic set if the storms were not categorized by ENSO intensity/phase. The total number of landfalls per year is about 5 in this case. Climatology says that the United States gets about 2 hurricanes per year (Landsea 2014); because this synthetic set is based on climatologically observed storm formation and formation, takes into account hurricanes as well as tropical storms. Two hurricanes per year is the average number of hurricanes making landfall based on climatology alone – this synthetic set takes into account tropical storms as well.

In summary, La Niña (strong, moderate and weak) tends to have more hurricanes make landfall than El Niño does. Specifically, strong La Niña has a slightly larger number of landfalls with weak La Niña even larger than that. When comparing El Niño, the weak El Niño phase has a slightly larger number of hurricanes as a whole. On the general scale, looking at La Niña, El Niño and Neutral, the neutral phase has the largest storm count, followed by La Niña then El Niño.

The time to landfall was analyzed by state and ENSO phase/hurricane intensity. The results are below.

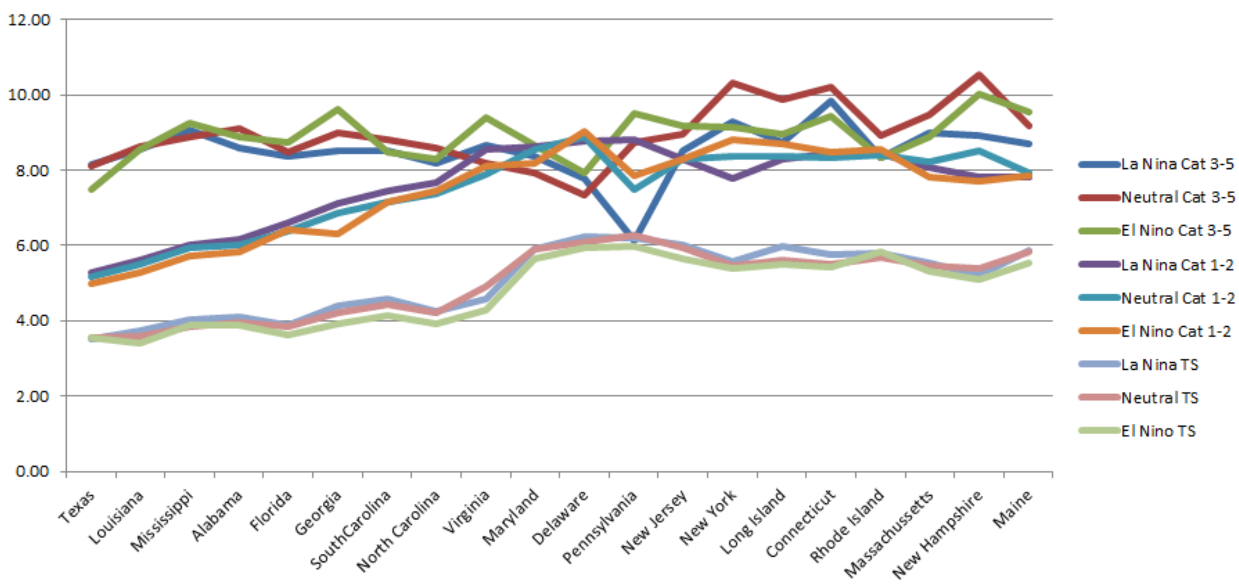

FIGURE 8 – Time to landfall per ENSO and hurricane intensity, 1950-2012

The correlation between hurricane intensity and time to landfall is easily visible. Tropical storms take the least amount of time between formation and landfall, followed by category 1-2 hurricanes and subsequently category 3-5 hurricanes after that. Interestingly, the data points drop significantly at Pennsylvania indicating that the time to landfall decreases from 8 to 6 days. My advisor and I hypothesize that this could be due to the east-west wind component in this region of the United States, or possibly the shape and length of the coastline for Pennsylvania. This outlier in the "pattern" could be a potential issue with the robustness of this average. Analyzing this hypothesis and outlying data point further is possible for future study, but was not analyzed here.

Next, the time to landfall frequencies dependent of ENSO phase were analyzed. The following histogram displays the right-skewed slope that is expected with the time to landfall frequencies. Only El Niño and La Niña phases are compared here.

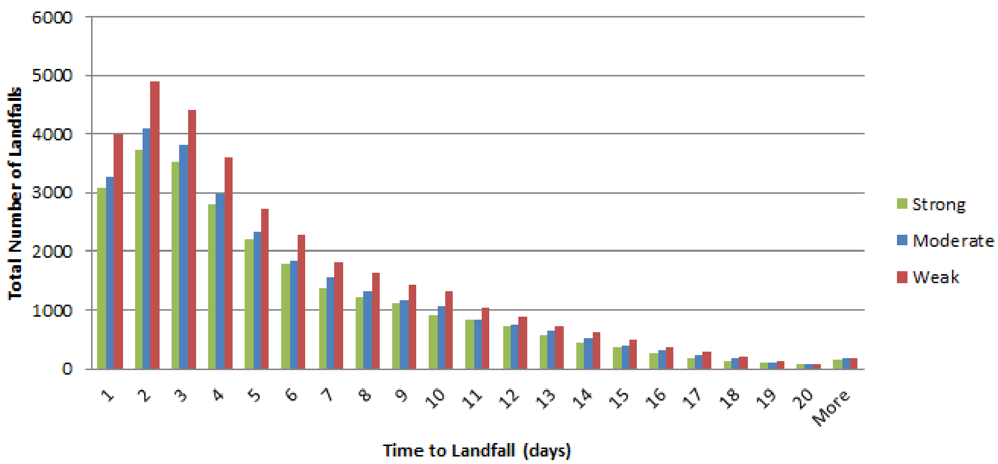

FIGURE 9 – Time to landfall frequencies during El Niño years, 1950-2012

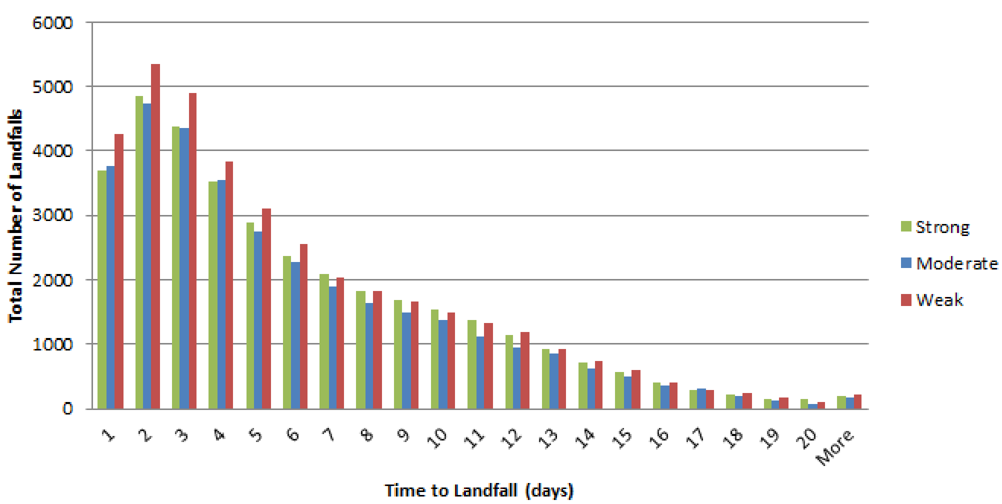

FIGURE 10 – Time to landfall frequencies during La Niña Years, 1950-2012

By first glance, it is shown again that the number of La Niña hurricanes (in each category) is greater than the number of El Niño hurricanes. Dissecting the El Niño frequencies, the largest frequencies in each bin is Weak El Niño. Logically this makes sense, because it is the phase that is closest to neutral. Knowing that El Niño is the least conducive for hurricanes, the stronger an El Niño phase is, the less frequent hurricane formation is during that phase. Hurricanes that have duration up to 6 days are more frequent during weak La Niña than during a moderate or strong La Niña. Beyond the 6 day mark, the frequencies between La Niña intensity seem to level out. Both El Niño and La Niña phases have a higher frequency of hurricanes during the first 6-7 days, and then taper off after that.

Dissecting the time to landfall even further, we can analyze the time to landfall during our categorized ENSO intensities by state. The following graph groups together Mississippi and Alabama, as well as all states north of North Carolina. Mississippi and Alabama share a very close and small coastline, and the small number of hurricanes making landfall north of North Carolina pushed my advisor and me to “lump” together all of these states for simplicity as well as improve sample size.

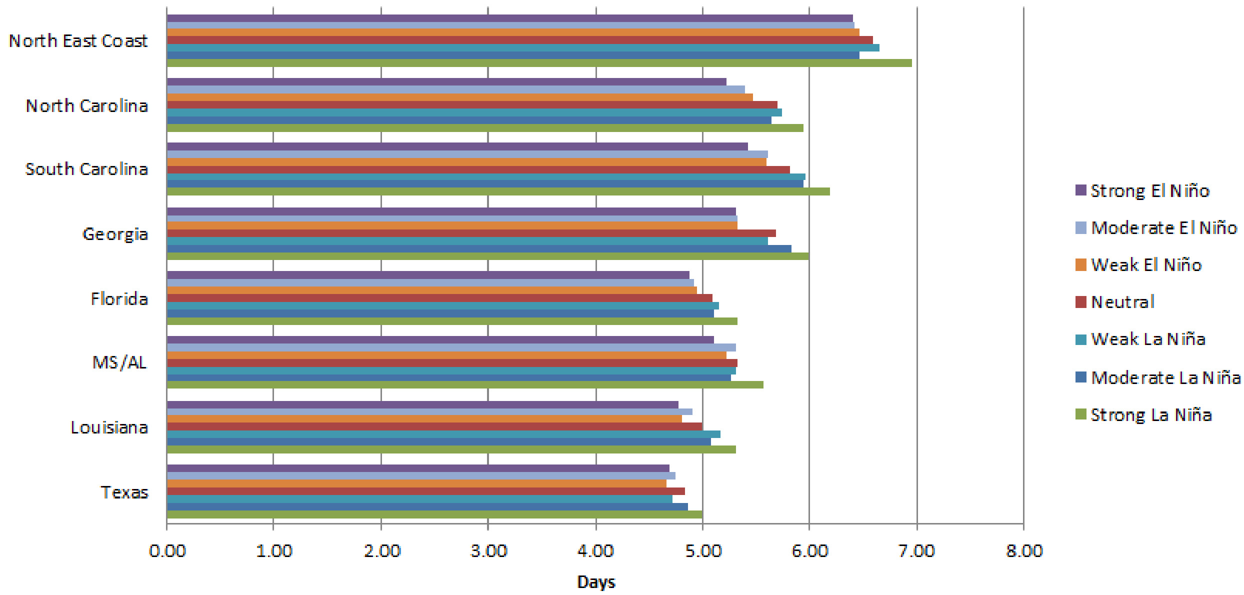

FIGURE 11 –Average Time to Landfall by ENSO Intensity/Phase, 1950-2012

The time to landfall for the North East Coast is the largest of the 8 regions, taking anywhere between 6.5-7 days. A Strong La Niña phase takes the longest at 7 days when looking at the east coast, validating that a Strong La Niña has the largest effect on hurricanes when compared to the behavior during a Neutral phase. In fact, Strong La Niña has the longest time to landfall in each state region. Texas has the shortest time to landfall, which makes sense because it is close to regions of hurricane formation. The time to landfall decreases with ENSO intensity – in other words, the longest time to landfall is during a Strong La Niña, then Moderate La Niña, and Weak La Niña. The cycle further decreases at the Neutral stage, and then continues to decrease in the order of a Weak El Niño, Moderate El Niño, and finally Strong El Niño.

Relationship between Time to Landfall and Distance

The average time between formation and landfall was calculated by state, as well as the average distance between formation and landfall. Previously, we discussed the distance and time to landfall based on ENSO intensity. Below, the same analysis is broken down further by state.

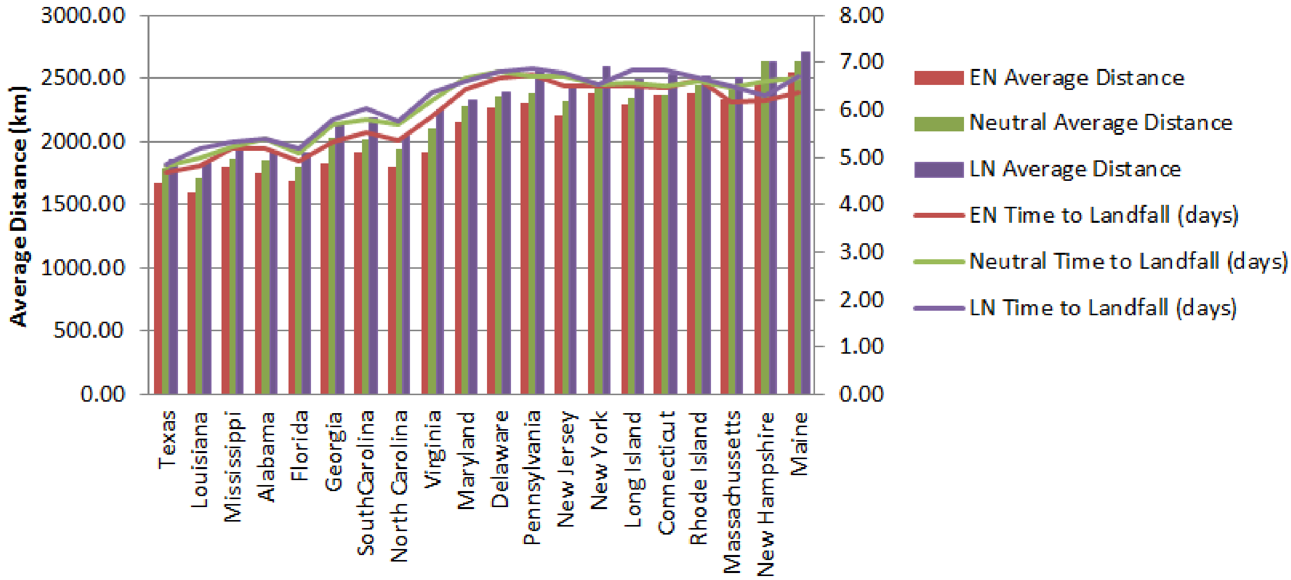

FIGURE 12 – Distance and Time to Landfall Relationships, 1950-2012

Typically speaking, the distance and time to landfall are a pretty linear relationship – the shorter the distance, the shorter it takes for a hurricane to make landfall. In Florida, the time to landfall is less than in adjoining states. North eastern states have a similar trend, where the distance is longer but the time to landfall is shorter. It is possible that these adjoining north eastern states have a shorter time to landfall because the long-lived Cape Verde storms typically recurve out to sea before making landfall in that region. Also, it was mentioned earlier in the results section that this could be due to the layout of the coastline, as well as the east-west wind component. When comparing the time to landfall trend lines based on ENSO phase, La Niña has a larger time to landfall by a fraction of a day and El Niño has the shortest time to landfall. The distance between formation and landfall is generally the longest during a La Niña phase and the shortest during an El Niño phase.

Hurricane Probability

Lastly, an analysis was conducted that looks at hurricane probability within 4 days warning based on ENSO state and hurricane intensity. Hurricane intensity/category is shorthanded "cat" in this graph. The results are shown below.

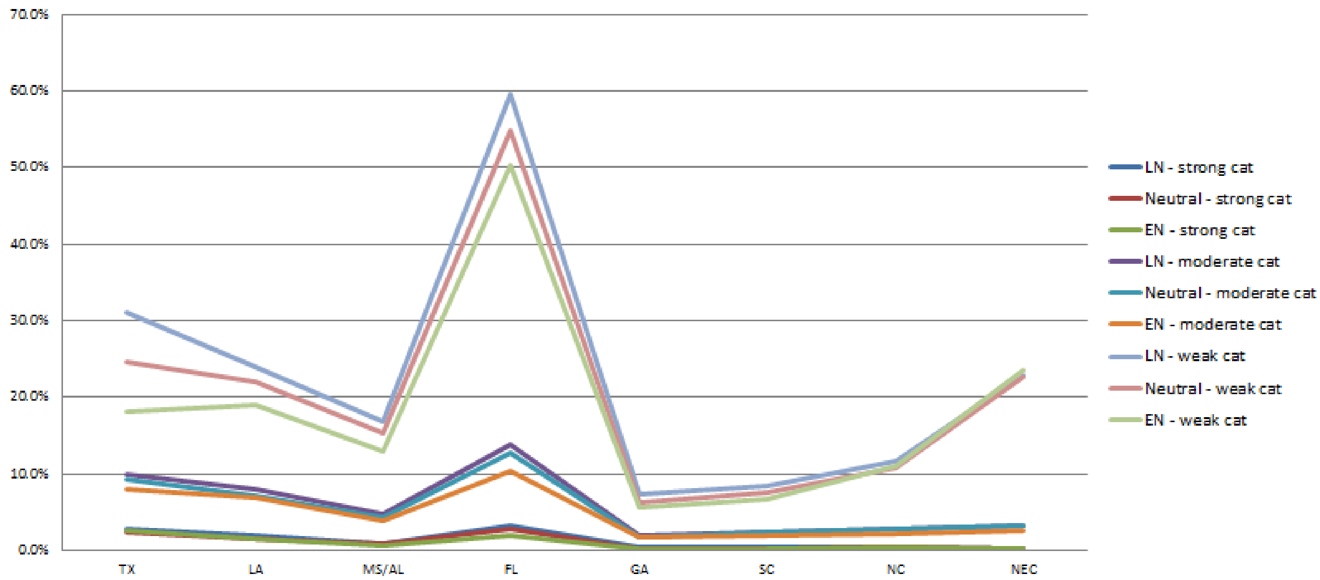

FIGURE 13 – The probability of a hurricane making landfall within 4 days warning based on ENSO state and hurricane intensity, 1950-2012

The 3 groups of lines show weak, moderate, and strong categories of hurricane intensity. For all 3 groups, there is a massive peak in hurricane probability over Florida. The graph is read like so: there is a 60% chance for a hurricane of weak intensity during La Niña within a 4 days' notice in Florida. In comparison to the other two groups, weaker hurricane intensities have a higher landfall probability - hurricanes making landfall during a La Niña phase have the largest probability all across the states. The probability for a hurricane decreases as hurricane intensity increases – the moderate intensity hurricanes have the next highest percentage for landfall probability across the states, followed by the strong intensity hurricanes. Because the strong intensities are so miniscule on this graph, they were examined in detail independently. The resulting graph is below.

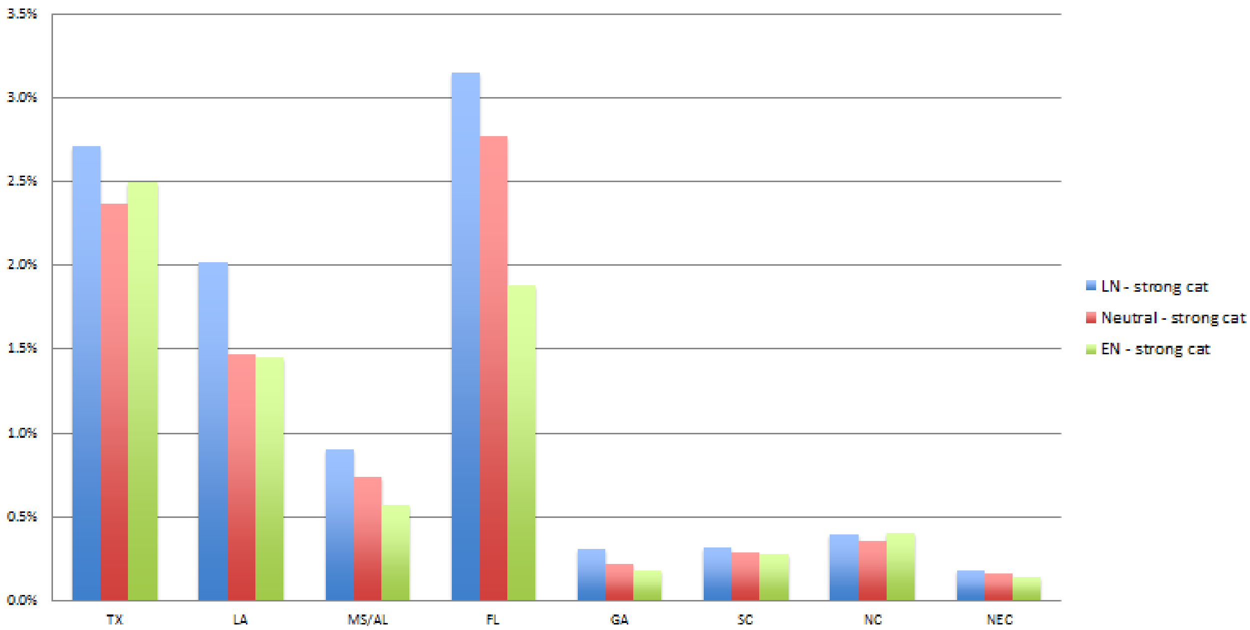

FIGURE 14 – The probability of a hurricane making landfall within 4 days warning during strong phases, 1950-2012

There is a higher percent chance for a strong intensity hurricane making landfall during a La Niña across the board, though it is on a small scale of 0.25%-3%. Florida has the highest chance of a high intensity hurricane making landfall during La Niña at ~3.2%. Comparing this number to the El Niño phase, which is only ~1.8%, strong intensity hurricanes during a La Niña have a larger probability of making landfall than strong intensity hurricanes during an El Niño. The areas of highest concern range from Texas to Florida. High intensity hurricanes, which fall between categories 3-5, are absolutely crucial to prepare for. A 4 days' notice to evacuate populations, reinforce buildings, and prepare the coastline for a potentially fatal hurricane is not lengthy by any means, and this region of the United States has the highest percentage of attracting this type of situation. In summary, there is an extremely small chance for a high intensity hurricane during these 3 ENSO phases within a 4 days' notice – however, this should not be taken lightly in states surrounding the Gulf of Mexico.

CHAPTER IV

CONCLUSION

Review of Results

The overall result is that both the average time to landfall and the distance between formation and landfall are not significantly impacted by an ENSO phase/intensity, though distance is more so impacted than time to landfall. Impacts on time to landfall and distance were noted in the results; however these differences are on the scale of a fraction of a day or hundreds of kilometers. States in the Gulf of Mexico region are more significantly impacted in terms of total landfalls per state. The number of landfalls per year is larger during La Niña phases than El Niño phases, which confirms previous case studies. The time to landfall is longer for higher category hurricanes, and slightly higher for La Niña versus El Niño phases. It takes longer for a hurricane to make landfall during a Strong La Niña, however this is only on the scale of a fraction of a day. Hurricane probability within a 4 day warning period is larger for weaker TC's, and decreases as the hurricane strengthens.

What This Means for Emergency Management

The whole point of this study was to help improve the emergency management system; not in terms of warning time for specific hurricanes, but in preparing for hurricane seasons during climatic events like ENSO. These findings can help forecasters prepare regardless of the intensity and phase of ENSO. Knowing that the time to landfall is almost unaffected by ENSO phase as well as the intensity of that phase is beneficial to their preparations. This also further validated that La Niña phases are more conducive for hurricane formation then El Niño phases are, and is also useful for hurricane season preparations. If the Emergency Management System can go into hurricane season knowing that La Niña will likely bring more hurricanes (and vice versa for El Niño), they can be prepared to give the public adequate warning times. Now knowing that the intensity of the ENSO phase does not make a severe difference in hurricane formation/landfall time, the Emergency Management System can use this information to prepare months in advance with the help of ENSO indices and predictions. To the best of our knowledge, there have not been previous case studies discussing the effects of ENSO on time to landfall. Though there is little ENSO signal, the results of this study are extremely important because of their door-opening results. The range of possible time to landfalls during this type of climatic event can be of such high use to the Emergency Management System, and can potentially save thousands of lives and millions of dollars in infrastructural damage.

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