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Trends in Location of Lifetime Maximum Intensity of Tropical Cyclones in the North Atlantic and West Pacific Oceans

Sarah Ann Bleakney

University of Tennessee - Knoxville, sbleakne@vols.utk.edu

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I am submitting herewith a thesis written by Sarah Ann Bleakney entitled "Trends in Location of Lifetime Maximum Intensity of Tropical Cyclones in the North Atlantic and West Pacific Oceans." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Kelsey N. Ellis, Major Professor

We have read this thesis and recommend its acceptance:

Henri D. Grissino-Mayer, Bruce A. Ralston

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Trends in Location of Lifetime Maximum Intensity of Tropical Cyclones in the North Atlantic and West Pacific Oceans

A Thesis Presented for the

Master of Science

Degree

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Sarah Ann Bleakney

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ABSTRACT

Tropical cyclones threaten coastal populations around the world each year. Thus, the climatology of tropical cyclones is an immediate research need, specifically to better understand their long-term patterns and elucidate their future in a changing climate. One important pattern that has recently been detected is the poleward shift of the lifetime maximum intensity (LMI) of tropical cyclones in the Northern Hemisphere. My study further assesses the recent spatial changes in the LMI of tropical cyclones in the Northern Atlantic and Western Pacific basins since 1964. I explored relationships between the intensity and location of LMI with respect to landfall location using the IBTrACS dataset and ArcGIS software. I found that different trends in LMI migration have occurred in individual ocean basins, specifically southerly movement in the North Atlantic and northerly movement in the Western Pacific. Separating the storms by intensity revealed that the strongest storms follow the general trend in their basin at a faster rate. The most intense tropical cyclones are reaching maximum intensity closer to landfall in the Western Pacific basin and farther away from landfall in the North Atlantic. This combination of a poleward shift of LMI and a smaller distance between LMI and landfall for the strongest storms in the Western Pacific basin may adversely affect coastal communities. The results confirm the previous finding that the strongest storms may experience the greatest changes in a warming climate.

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CHAPTER ONE

INTRODUCTION

A cyclone is a “closed, generally circular, rotation of air spinning in a counterclockwise direction in the northern hemisphere” (Elsner and Kara 1999). Tropical cyclones (TCs) are a specific sect of cyclones that develop over warmer water in the tropics. A TC is classified as a “hurricane” in the North Atlantic basin or “typhoon” in the Western Pacific when it reaches a wind speed 33 m/s (65 knots). This study focuses on TCs that occur in two relatively active basins: the North Atlantic and the Western Pacific. North Atlantic TCs occur between the continents of North America on the west and Europe and Africa on the east. Western Pacific TCs occur north of the equator between 100° east and 180° east (Elsner and Kara 1999; Knapp et al. 2010). The North Atlantic basin experiences 11% of global TC activity, and over half of these TCs mature into hurricanes (Elsner and Kara 1999). The official North Atlantic hurricane season spans from June to November, with the most active period falling from August to October (Kossin and Camargo 2009). The Western Pacific basin experiences 32% of global TC activity, making it the most active ocean basin (Ritchie and Holland 1999). The official Western Pacific typhoon season spans from May to October, with the most active period occurring from July to September (Neumann 1993; Ritchie and Holland 1999); however, TCs can occur at any time during the year in this basin.

TCs are tied with earthquakes as the natural hazard most responsible for the loss of life and property (Anthes 1982; Emanuel 1987). Some studies have suggested hurricanes are the costliest natural catastrophe in the United States (Pielke and Landsea 1998; Emanuel 2005). Deviations from expected typhoon patterns can leave countries in severe drought while other countries may suffer multiple record-breaking storms in one year (Wu et al. 2005). These observations and occurrences justify further research in the field of TC climatology to better understand and prepare for these natural disasters.

1.1 Hurricane Climatology

Hurricane climatologists are interested in long-term variability in TC characteristics, such as storm frequency, intensity, track, genesis location, and duration (Kossin et al. 2010). These characteristics vary naturally over time based on large-scale climatic oscillations (Kossin et al. 2010). These characteristics also vary because of the warming of the global climate in recent decades, which is an object of recent study (Elsner et al. 2008; Kossin et al. 2014).

Large-scale climate oscillations affect TC frequencies, tracks, and intensities (Kossin et al. 2010). Oscillations influence TCs through sea surface temperature, vertical wind sheer, and atmospheric steering currents (Goldenberg and Shapiro 1996; Maloney and Hartmann 2000; Elsner 2003; Xie et al. 2005; Kossin and Vimont 2007; Camargo et al. 2009; Klotzbach 2010; Kossin et al. 2010). For example, the North Atlantic Oscillation (NAO) influences the tracks of North Atlantic TCs by steering the storms and determining where they will begin to recurve in the ocean (Elsner et al. 2000). Elsner et al. (2000) the Gulf of Mexico coastal area is more susceptible to major TC landfalls during relaxed NAO phases, while the East Coast is more susceptible during excited NAO phases (Elsner et al. 2000). Another example is the El Niño-Southern Oscillation (ENSO), which influences the frequency of the storms. During an El Niño year, TCs are more common in the Pacific and less common in the Atlantic (Shaman et al. 2009; Wang 2004).

As the climate warms, related trends in TC frequency are not apparent (Kossin et al. 2014); however, recent finding suggests global climate change may be influencing TC intensity, track, genesis location, and duration. Alterations of TC intensity include changes in the location of highest intensity (Kossin et al. 2014) and an increase in the strength of the most intense TCs (Elsner et al. 2008).

1.2 Changes in Intensity

An increase in TC intensity coincides with an increase in sea surface temperature (SST) (Emanuel 1987). As global temperatures rise, SSTs increase and provide TCs with energy through the latent heat of vaporization (Emmanuel 1987). The average number of strong TCs per year has increased with a rise in SST (Elsner et al. 2008). Mean intensity trends are not clear, but evidence suggests the strongest hurricanes are getting stronger in the North Atlantic basin (Elsner et al. 2008). The lifetime maximum wind speeds of the strongest storms in the Western Pacific basin are also increasing, but the greatest increase is seen in the North Atlantic basin (Elsner et al. 2008).

Spatial changes in intensity have also been identified. The locations where TCs are reaching their maximum intensities are changing because the average annual location of lifetime maximum intensity (LMI) is shifting poleward (Kossin et al. 2014). This trend could potentially be linked to the poleward expansion of the tropics, which are believed to be shifting toward the poles at about 1° latitude per decade (Reichler 2009). As a result, the region most compatible for TC development is also moving poleward (Kossin et al. 2014). Kossin et al. (2014) called for future studies to examine the poleward shift of LMI and its relationship to tropical expansion.

This study extended the work of Kossin et al. (2014) to assess recent (1964–2014) spatial changes in LMI in relation to TC intensity and landfall location. I focused on two specific trends in LMI: the latitudinal shift of LMI relative to storm intensity and LMI location relative to landfall. The most intense hurricanes cause the largest proportion of TC-related damage, and an understanding of spatial and temporal patterns and trends in their intensities is imperative. TCs reaching LMI closer to landfall locations may pose a greater threat than those decaying well before landfall. My study is the first to analyze LMI while considering the potential effects on coastal communities.

1.3 Research Questions and Objectives

The objective of my study was to assess recent (1964–2014) spatial changes in the LMI of TCs in relation to TC intensity and landfall location in the North Atlantic and Western Pacific basins. This objective was achieved by addressing two research questions:

- Question 1: As the LMI of TCs shifts in latitude in the North Atlantic and Western Pacific basins, do variations exist in the rate of change for TCs of different intensities? Because the strongest TCs are demonstrating the largest change in intensities, do the strongest TCs also see the largest latitudinal shift in LMI position?
- Question 2: Where does LMI occur relative to different landfall locations in the North Atlantic and Western Pacific basins? With the shifts in the latitude of LMI, is LMI occurring closer to the coastline?

CHAPTER TWO

LITERATURE REVIEW

2.1 Measuring TC Intensity

Major landfalling hurricanes (Category 3 and higher on the Saffir-Simpson Scale) are of specific concern to society because 80% of TC damage is caused by the strongest 20% of storms (Elsner et al. 2000). Storm dynamics allow each TC to reach the highest maximum intensity energetically possible and therefore also maximum destructive power (Emanuel 1987). To adequately prepare for this threat, we must estimate future trends in TC intensity. The intensity of a TC directly relates to the destructive power of the storm and is quantified through its central pressure or its maximum sustained wind speed. Maximum wind speed and minimum pressure are strongly related and are often used interchangeably to represent intensity. For example, wind speed and pressure have a correlation of 0.96 in the North Atlantic basin from 1998 to 2005 (Brown et al. 2008) and a correlation of 0.92 in the Western Pacific basin from 1947 to 1974 (Atkinson and Holliday 1977).

2.1.1 Lifetime Maximum Intensity

In addition to studying the intensity of a storm throughout its entire lifetime, an important TC characteristic is the greatest intensity the TC reaches, or LMI. Kossin et al. (2014) found that focusing on the LMI of a TC reduced the uncertainty inherent in historic TC intensity estimates. While accurate historic measures of storm intensity may be hard to attain, LMI is a more robust variable because the timing of LMI is less sensitive to data errors (Kossin et al. 2014). Kossin et al. (2014) analyzed a 31-year span from 1982 to 2012 and discovered the LMI of TCs recently has reached higher latitudes. This trend is consistent across hemispheres with slight variations in the amount of movement in each basin. Globally, the average poleward shift is between 53 and

62 km per decade (statistically significant), which corresponds to approximately 1° latitude per decade (Kossin et al. 2014).

2.1.2 Potential Intensity

Potential Intensity (PI) is a theoretical upper limit of the maximum intensity of a TC based on the local ambient thermodynamic conditions, and can be estimated using temperature and moisture data (Kossin and Camargo 2009). The thermodynamic efficiency of a TC is tied to SST because warmer water facilities the growth of a deep moist convecting layer, while colder water only allows for a shallow layer (Emanuel 1987). With all other variables held constant, PI is directly related to the SST below the storm (Emanuel 1991; Holland 1997; Bister and Emanuel 2002; Elsner et al. 2008). For example, TC wind speed increases 15–20% for an increase in SST of 3° C (Emanuel 1987).

PI and vertical wind shear are known to influence the LMI of a TC (Emanuel 1999; Knaff et al. 2004; Zhang and Tao 2013). Greater shear and a lower PI would encourage a TC to decay, whereas lower shear and a higher PI would encourage intensification. Therefore, a shift in the shear and PI would likely result in a shift in the LMI. Kossin et al. (2014) found decreased shear in the subtropics and increased shear in the deep tropics from 1980 to 2010. Likewise, PI has increased in the subtropics and decreased in the deep tropics (Kossin et al. 2014). These changes in PI and vertical wind shear shift the region most compatible for TC development poleward (Kossin et al. 2014).

2.1.3 Power Dissipation Index

Emanuel (2005) defined an index of the potential destructiveness of hurricanes based on power dissipation and termed the power dissipation index (PDI), which is related to hurricane intensity. The PDI has been increasing over time because of longer storm durations and greater

TC intensities (Emanuel 2005). In fact, over the past 30 years, the destructive potential of TCs has nearly doubled. Models predict as temperatures rise with global climate change, the potential destructiveness and maximum intensity of TCs will increase because of the strong relationship between PDI and SST (Emanuel 1987; Henderson-Sellers et al. 1998; Emanuel 2005). This strong relationship between PDI and SST was found in both the North Atlantic basin ($r^2 = 0.65$) and the North Pacific basin ($r^2 = 0.63$). Theoretically, the LMI should increase by 5% with an increase in ocean temperature of 1° C (Emanuel 2005). This increasing destructiveness, coupled with an increase in the coastal population, presents an even larger threat to life and property from TCs in coastal communities (Pielke et al. 2003).

2.1.4 Spatial Patterns

According to the theory of PI, the maximum intensity of a TC is defined and limited by factors in the local ambient environment, including SST and regional climatic changes (Emanuel 1986; Holland 1997; Kossin et al. 2000; Kossin and Camargo 2009). Based upon this theory, global climatological changes can therefore affect the span of PIs, potentially expanding the range to include even higher intensities. SST and PI in the North Atlantic have been increasing along with the TC intensity distribution during summer since 1980 (Kossin and Camargo 2009). SST and PI likely fluctuate in tandem because PI is known to influence the distribution of TC intensities by setting the upper limit of maximum intensity (Emanuel 2000; Kossin et al. 2000; Wing et al. 2007; Kossin and Camargo 2009). However, a rise in SST and PI cannot be specifically linked to a rise in the intensity distribution (Kossin and Camargo 2009).

The location of TC development plays a part in its eventual intensity and landfall location (Kossin and Camargo 2009). TCs that form farther from land will likely have a longer path and, therefore, increased duration. TCs intensify, on average, at a rate of about 12 m s^{-1} each day. TCs with longer paths have a greater window of opportunity to increase their intensity over warm SSTs and become major hurricanes, linking TC duration directly to TC intensity ($r^2 = 0.74$) (Emanuel 2000; Emauel 2005; Kossin et al. 2000; Emanuel 2005; Kossin and Vimont 2007; Kossin and Camargo 2009). TCs that mature into hurricanes in the eastern portion of an ocean basin make landfall at higher latitudes, whereas TCs that form farther west are more likely to intersect the coast at lower latitudes (Elsner et al. 2000).

Previous research has identified a relationship between TC track characteristics and intensity. Some studies have focused on the relationship between the type of track (e.g., recurving) and intensity. Evans and McKinley (1998) specifically studied the relationship between path recurvature and LMI. Track types were classified based on shape and point of recurvature. A recurving TC is one traveling west near the equator and then traveling east as it heads toward the poles (Evans and McKinley 1998). In the North Atlantic, 28% of TCs recurve while 31% of TCs recurve in the Western Pacific (Evans and McKinley 1998). The results suggested more intense TCs, as well as most systems in the Western Pacific, reach LMI before recurvature, and weaker storms are more likely to reach LMI during recurvature (Evans and McKinley 1998). One half to two-thirds of TCs never return to their peak level of intensity after recurvature. Recurvature signals that the TC is changing internally. TCs forming in the Caribbean and the Gulf of Mexico tend to have a northward track component, while those forming across the span of the equatorial region of the Atlantic tend to exhibit recurvature in their paths (Kossin et al. 2000). This link between intensity and timing of recurvature can help forecasters predict intensity based on track type. Researchers stress the importance of a deeper understanding of TC tracks, both for forecasting landfalls and for understanding how local climate may affect storm intensity (Kossin et al. 2014).

2.2 TCs and Long-term Climate Variability

TC intensity is related to large-scale climate oscillations (Kossin et al. 2010). Climate oscillations are regional to global in scale and undulate between a range of predicted values over scales of decades to centuries. Oscillations guide TCs through vertical wind sheer and atmospheric steering currents (Goldenberg and Shapiro 1996; Maloney and Hartmann 2000; Elsner 2003; Xie et al. 2005; Kossin and Vimont 2007; Camargo et al. 2009; Klotzbach 2010; Kossin et al. 2010). The predominant oscillation affecting a specific TC depends on the location of the TC (Kossin et al. 2010). ENSO and Atlantic Meridional Mode (AMM) regulate TCs in the North Atlantic, the NAO affects storms forming off of Cape Verde, and the Madden-Julian oscillation (MJO) affects storms in the Gulf of Mexico (Kossin et al. 2010). In the Western Pacific basin, TCs are most affected by ENSO (Camargo and Sobel 2005). El Niño years result in larger and more intense TCs than La Niña years. The year immediately after an El Niño event is typically less active over the entire Western Pacific basin, whereas the year after a La Niña event has an increase in TC activity (Chan 2000).

Additional spatial patterns evident in TCs may not be associated with a specific oscillation. While investigating historical patterns, Elsner et al. (2000) found a “spatial covariability in hurricane activity across latitudes,” meaning hurricane activity in the higher latitudes is greater than normal during a period when lower latitude activity is less than normal, and vice versa. This relationship is statistically significant and can be verified across seasonal and decadal time scales (Elsner et al. 2000).

2.3 Expanding Tropics and Influence on TCs

Researchers suggest the tropics and subtropics are expanding; however, one of the first obstacles is defining the tropics and subtropics (Reichler and Held 2005; Fu et al. 2006; Hudson et al. 2006; Hu and Fu 2007; Archer and Caldeira 2008; Seidel et al. 2008; Lucas et al. 2013). Because the border between the tropics and subtropics is a gradual change rather than a definitive line (Reichler 2009), the regions can be difficult to separate. Opinions differ on the area constituting each region as well as how much change has actually occurred. The subtropics are sometimes defined as the area poleward of the tropics of Cancer and Capricorn to the 38th parallels (Lucas et al. 2013), whereas the tropics would be the area within the tropics of Cancer and Capricorn. The subtropics can also be defined as the region between the polar jets or between the easterlies and westerlies (Reichler 2009). The subtropics are sometimes generalized as lying between the Hadley cell and the polar front (Lucas et al. 2013). These definitions are subject to change because the Hadley cell fluctuates with the seasons (Mitas and Clement 2005).

Various proxies are used for studying the expanding tropics, ranging from outgoing long wave radiation datasets collected by satellites to precipitation data (Lucas et al. 2013). The expansion of the tropics was likely first studied by Rosenlof in 2002, using the geographical shift of the Brewer-Dobson circulation, specifically the upwelling in the tropics. Rosenlof (2002) calculated an expansion value of 3° latitude between the years 1992 and 2001, likely an inflated value because of observational uncertainty. Reichler and Held (2005) expanded on this research by analyzing tropopause height through radiosonde data and found a smaller value of 0.4° latitude per decade since 1979. These studies generated interest in the subject, and subsequent studies examined the expanding tropics and subtropics using various data, compiling a range of results (Reichler 2009). Fu et al. (2006) analyzed tropospheric temperatures and found a widening of the subtropics of 0.7° latitude per decade. Hudson et al. (2006) found a 1° latitude per decade expansion of the tropics in the northern hemisphere using total ozone. Seidel and Randel (2007) studied tropical expansion using tropopause height, estimating an expansion range from 1.8° to 3.1°. Using outgoing longwave radiation through satellite sensors and mean meridional circulation, Hu and Fu (2007) estimated expansion values of 1.5° and 1.0° latitude per decade, respectively. Two studies used jet stream separation, one discovering an expansion of 0.3° latitude per decade (Archer and Caldeira 2008) and another an expansion of 1.0° (Seidel et al. 2008). This range of values results from different methods and data sources, as well as observational uncertainties. Excluding some of the extreme outliers, the general consensus is that the tropics are expanding at the rate of 1° latitude per decade (Reichler 2009).

The expanding tropics and subtropics will likely have numerous consequences. Because the subtropics are among the driest regions in the world, this expansion widens the threat of drought to locations that border the expanding subtropics (Lucas et al. 2013). Some models suggest the increase in latitudinal width of the Hadley Cell is a response to an increase in global temperatures (Frierson et al. 2007). Long-term effects may include changes in ocean circulation, potentially causing various feedbacks in marine ecosystems, tropospheric climate, and biogeochemical cycles, which may lead to irreversible climate change (Lovelock 2006). The expansion of the tropics may also affect the development, tracks, and geographical reach of TCs (Seidel et al. 2008). A northward shift in extratropical storm tracks is expected (Lucas et al. 2013).

The expansion of the tropics has progressed faster than predicted by models, displaying a lack of understanding about the processes behind the expansion (Seidel et al. 2008). Theories suggest multiple causes for this poleward expansion, including anthropogenic aerosols, stratospheric ozone depletion, and an increase in greenhouse gases (Lucas et al. 2013). The primary driver of tropical and subtropical expansion is not yet clear (Lucas et al. 2013), but the causes may be linked to anthropogenic contributions (Frank and Young 2007). The potential link between the poleward shift of both the LMI and the tropics is a motivation for hurricane climatologists to discover the forcing mechanisms behind this expansion of the tropics and attempt to estimate its effects (Kossin et al. 2014).

2.4 TCs and Climate Change

An important question for hurricane climatologists is the effect of global climate change on TC activity, specifically the frequency and intensity of storms. A rise in the frequency of TCs seemingly coincides with a global increase in SST; however, it is argued that the TC data are not reliable enough to support this claim (Elsner et al. 2008). Intensity trends are more certain. Elsner et al. (2008) found TCs are becoming stronger in recent years (1981–2006); more specifically, the strongest storms are getting stronger. The trend was most prominent in the North Atlantic basin, although this strengthening of the largest TCs can be seen globally. This is consistent with the hypothesis that as the ocean water warms, more energy is available to fuel TC winds. Elsner et al. (2008) found the median value of LMI of a TC has not seen any change from 1981–2006, and the mean has increased in the North Atlantic basin only. The largest increase in intensity is seen in the 9th decile. As a result, the average number of strong cyclones rose from 13 to 17 from 1981–2006, related to an increase in SST of 1 °C (Elsner et al. 2008). Therefore, while overall frequency trends are not clear, the frequency of the strongest storms is increasing.

Emanuel (1987) modeled TCs in a future warmer climate and found an increase in TC intensity that coincided with an increase in temperature. An increase in global mean temperatures would raise global SST and, as a result, TC intensity, because SST is directly related to PI. Based on the results obtained by Emanuel (1987), a 40–50% increase in CO_2 content would double the destruction of a TC. Knutson et al. (2010) ran a high-resolution model and found greenhouse warming to coincide with a 2–11% increase in the average TC intensity by 2100.

A final effect of climate change on TCs is the poleward shift of LMI. Kossin et al. (2014) found that the LMI is shifting poleward at an average rate of 1° of latitude per decade when considering all global TCs. The distance of the latitudinal shift away from the tropics varies between each basin. The North Indian Ocean is the only basin in which the LMI of TCs is not shifting toward the poles. LMI in the Western Pacific has the strongest poleward trend, and LMI in the Eastern Pacific basin experiences only slight poleward shifts. The South Pacific and South Indian Ocean both exhibit strong poleward trends. The North Atlantic experiences no significant trend. Kossin et al. (2014) listed several reasons for future research in this study area. This shift may alter precipitation totals in affected regions; some areas may experience drier conditions while others may experience unexpected flooding (Jiang and Zipser 2010; Lam et al. 2012). Further, TCs may strike communities not structurally prepared for the natural disaster (Peduzzi et al. 2012). Increases in coastal community hazard exposure and mortality risk from TCs are expected (Peduzzi et al. 2012) because of these combined changes in frequency and intensity.

CHAPTER THREE

DATA AND METHODS

3.1 Data

Data were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) maintained by the National Oceanic and Atmospheric Administration National Centers for Environmental Information (Knapp et al. 2010). This historic global “best track” dataset contains information on location, intensity, duration, size, and more (Knapp et al. 2010). This dataset contains the best track data in 6-hour increments for TCs around the world beginning with the year 1851 in the North Atlantic basin and 1884 in the Western Pacific basin. The TC data in IBTrACS are obtained from various sources, including meteorology departments in China, Japan, Australia, France, and more (Knapp et al. 2010). IBTrACS combines TC data from around the world into a single website and offers the data in multiple formats.

Because HURDAT is the main source for storms in the North Atlantic basin, IBTrACS has similar flaws to those of HURDAT (Knapp et al. 2010). Frequency and intensity errors are known to exist in the dataset. Some TCs went unobserved prior to the invention of the satellite, causing an increase in frequency over time in the dataset. Intensity errors also exist, especially earlier in the dataset. Because intensity is uncertain, duration is then also uncertain because the moment a storm reaches a certain intensity (i.e., wind speeds of tropical storm or hurricane intensity) must be known to accurately identify the moment of cyclogenesis (Kossin et al. 2014). The invention of weather satellites in the 1960s greatly improved the detection and tracking of TCs by using visible and infrared sensors (Jarvinen et al. 1984).

My study used data spanning 1964 to 2014 for the North Atlantic basin (Figure 1a) and the Western Pacific basin (Figure 1b). The Western Pacific basin dataset contained multiple

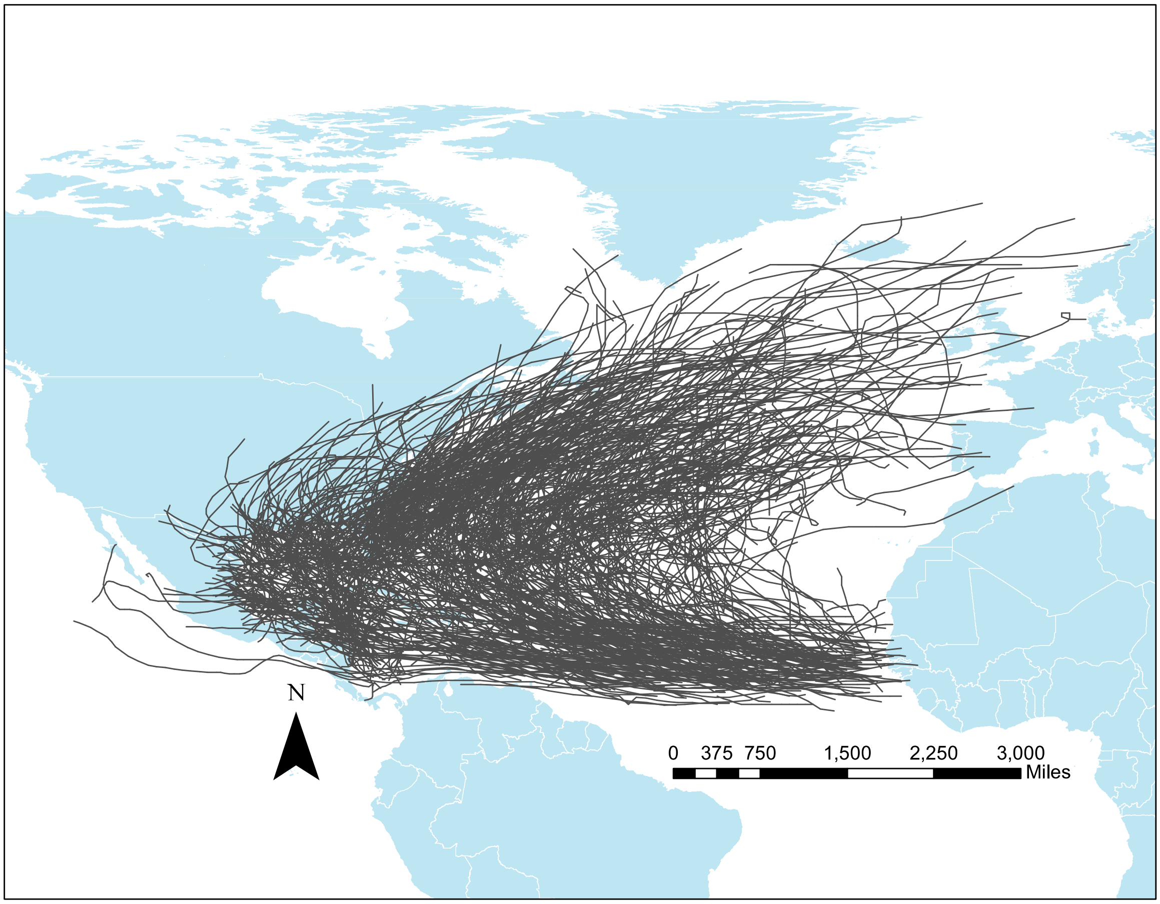

Figure 1a. North Atlantic TC tracks from IBTrACS spanning 1964 to 2014 (n = 21,265).

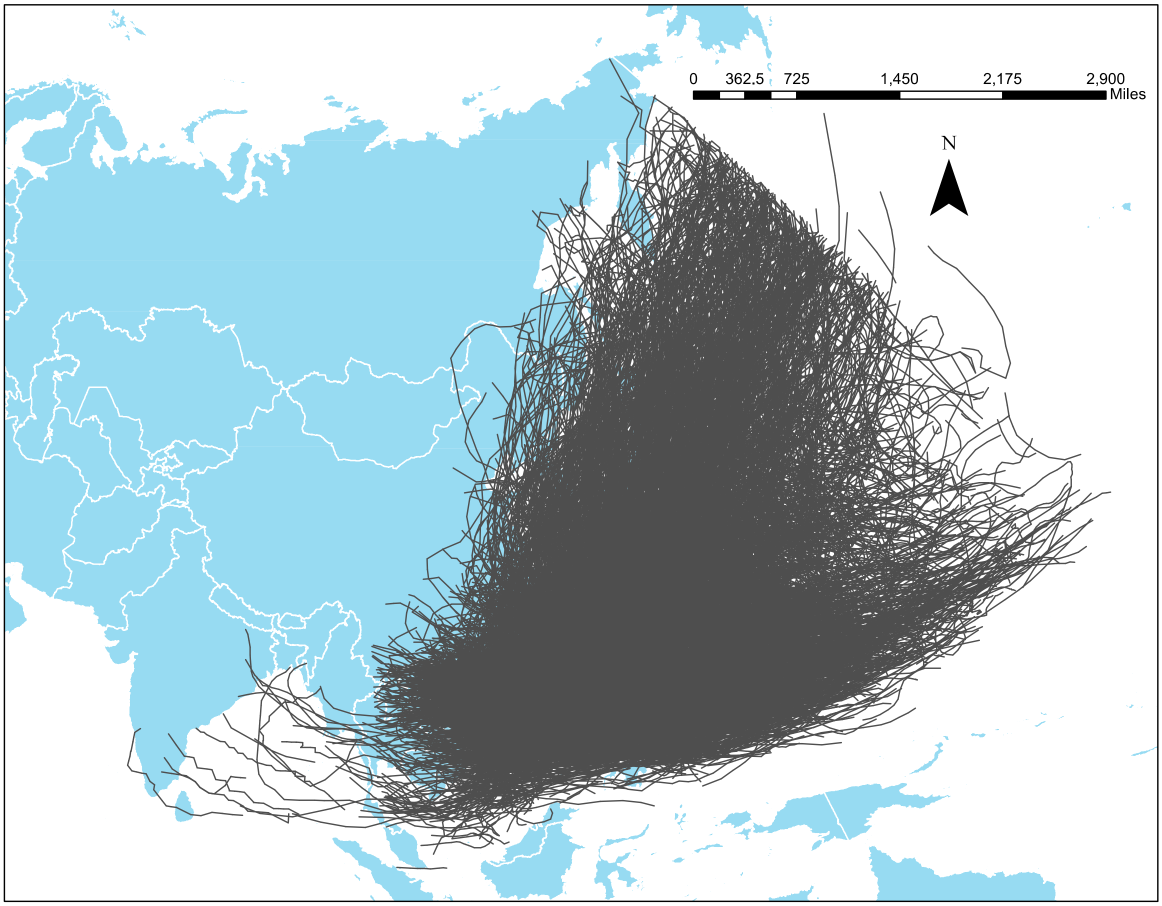

Figure 1b. Western Pacific TC tracks from IBTrACS spanning 1964 to 201 (n = 54,777).

years without intensity data, namely from 1964 to1976, which could not be included in this study. Therefore, statistics for the Western Pacific basin begin in 1977. The Global Administrative Areas shapefile was used for global coastlines.

3.2 Methods

For this study, I used ArcGIS (version 10.1) to analyze trends in the location and timing of the LMI of TCs in the North Atlantic and Western Pacific basins. LMI was calculated using the wind measurements included in the IBTrACS dataset through a series of functions in ArcGIS that selected the last, most intense wind speed (Figure 2). TC paths in the North Atlantic were projected using the North America Lambert Conformal Conic projection, and TC paths in the Western Pacific basin were projected using the Asia Lambert Conformal Conic projection.

To address question 1, the latitude of each LMI was calculated in the attribute table of the shapefile. These latitudes were then arranged over time to investigate trends in the location where TCs of various intensities reach their LMI. I analyzed the annual average latitude over time for both hemispheres combined and then separately using a ten-year moving average to enhance the overall trend by averaging out anomalies and cyclical climate signals. Next, I used quantile regression was used to determine if intensities in different quartiles were shifting more or less poleward than their counterparts in other quartiles. In this linear regression, time was the independent variable and the mean latitude of the LMI was the dependent variable. I separated the quartiles based on LMI values, with the strongest storms being in quartile 4 and the weakest storms in quartile 1. For each quartile, the annual average LMI location and line of best fit were calculated and uniquely displayed on a graph. I further broke down this dataset into deciles to discover trends in the outliers of the dataset, which have shown the most change in intensity in previous studies (Elsner et al. 2008).

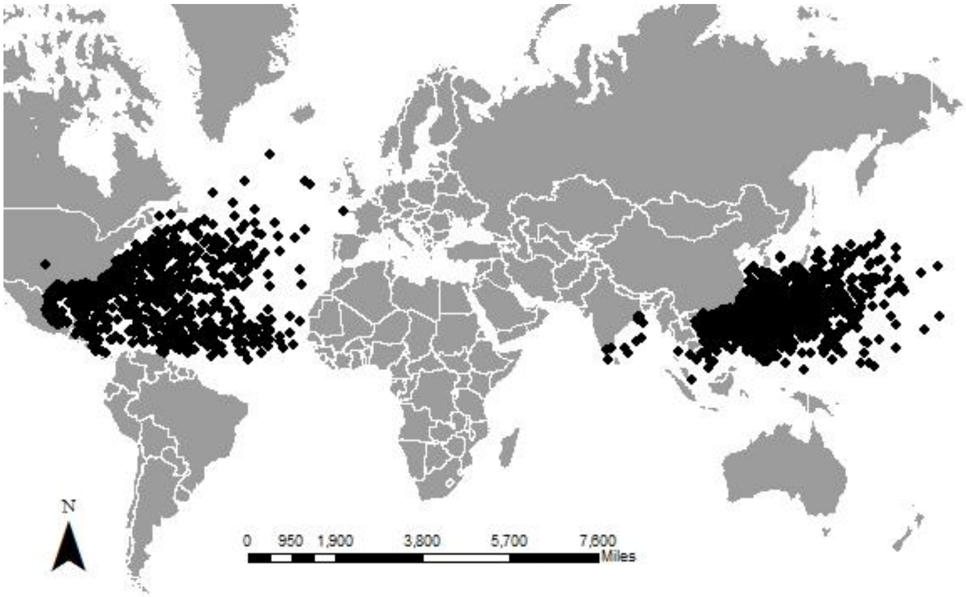

Figure 2. LMI location of hurricanes (Category 1 strength and greater) in the North Atlantic basin (n = 839) and the Western Pacific basin (n = 997).

To address question 2, I plotted LMI and landfall location of each landfalling TC within the period in ArcGIS. The IBTrACS dataset provides multiple line segments for each TC that together make up the total TC track. These line segments were dissolved into one single TC track based on serial number, creating one complete storm track per TC. I then used the select by location function in ArcGIS to extract TC tracks that intersected land. The distance from each LMI to landfall was measured in an edit session using the measure tool that traced TC tracks exactly.

A portion of TCs reached LMI over land in both the North Atlantic (12) and Western Pacific (10) basins. Some TCs made landfall before returning to the ocean to reach LMI over the North Atlantic (18) and Western Pacific (28) basins. Additionally, the Western Pacific basin dataset contained multiple years without intensity data, namely from 1964–1976. My study focused on the remaining TCs in the North Atlantic (171) and Western Pacific (356) basins that reached LMI before landfall.

I reordered and analyzed distances from LMI to landfall to determine trends over time in how far storms reached LMI from their eventual landfall location. Linear regression evaluated the strength of the relationships, using time as the independent variable and distance from landfall as the dependent variable. I calculated an average annual distance for all TCs using a pivot table and plotted in a line graph. The average annual distances were then analyzed by basin using linear regression. Finally, I split the average annual distances into quartiles and then deciles based on TC intensity, and once again tested for a linear trend. The slope, r^2, and p-value were calculated and recorded for each regression.

CHAPTER FOUR

RESULTS

4.1 Latitudinal Shift of LMI

On average, the LMI of TCs is shifting south at a significant ($p < 0.05$) rate of 0.99 (r^2 = .299) degrees of latitude per decade (Figure 3a). This southerly trend could be skewed due to issues in the Western Pacific basin dataset, specifically the missing data from the years 1964–1976. Because hurricanes in the Western Pacific basin generally reach LMI farther south, the inclusion of Western Pacific LMI latitude in the year 1977 brings the average latitude down, influencing the southern trend. Therefore, it is helpful to view the basins separately. When separated by basin, the LMI shifted south significantly ($p < 0.05$) at 0.60 degrees of latitude per decade ($r^2 = 0.15$) in the North Atlantic basin (Figure 3b) and shifted north at 0.30 degrees of latitude per decade ($r^2 = 0.04$) in the Western Pacific basin (Figure 3c).

The data were then subset to include only TCs of Category 1 hurricane strength (≥ 33 m/s or 65 knots) and greater in the North Atlantic, and TCs of typhoon strength (≥ 33 m/s or 64 knots) in the Western Pacific. The strongest storms were chosen for further analysis because they pose the greatest threat to coastal communities, and they show the greatest change in a changing climate (Elsner et al. 2008). For simplicity, when discussed as a combined set of storms, this subset is referred to as hurricane strength or greater. This dataset was used for the remainder of the analysis. Overall, the hurricanes reached their LMI farther south at a significant ($p < 0.05$) rate of 1.86 degrees of latitude per decade ($r^2 = 0.39$). This could once again be a result of adding the Western Pacific TCs part way through the analysis. Dividing the hurricanes into separate basins decreased the r^2 but highlighted the different patterns occurring in each basin. The LMI of hurricanes in the North Atlantic basin shifted south at a rate of 1.37 ($r^2 = 0.24$)

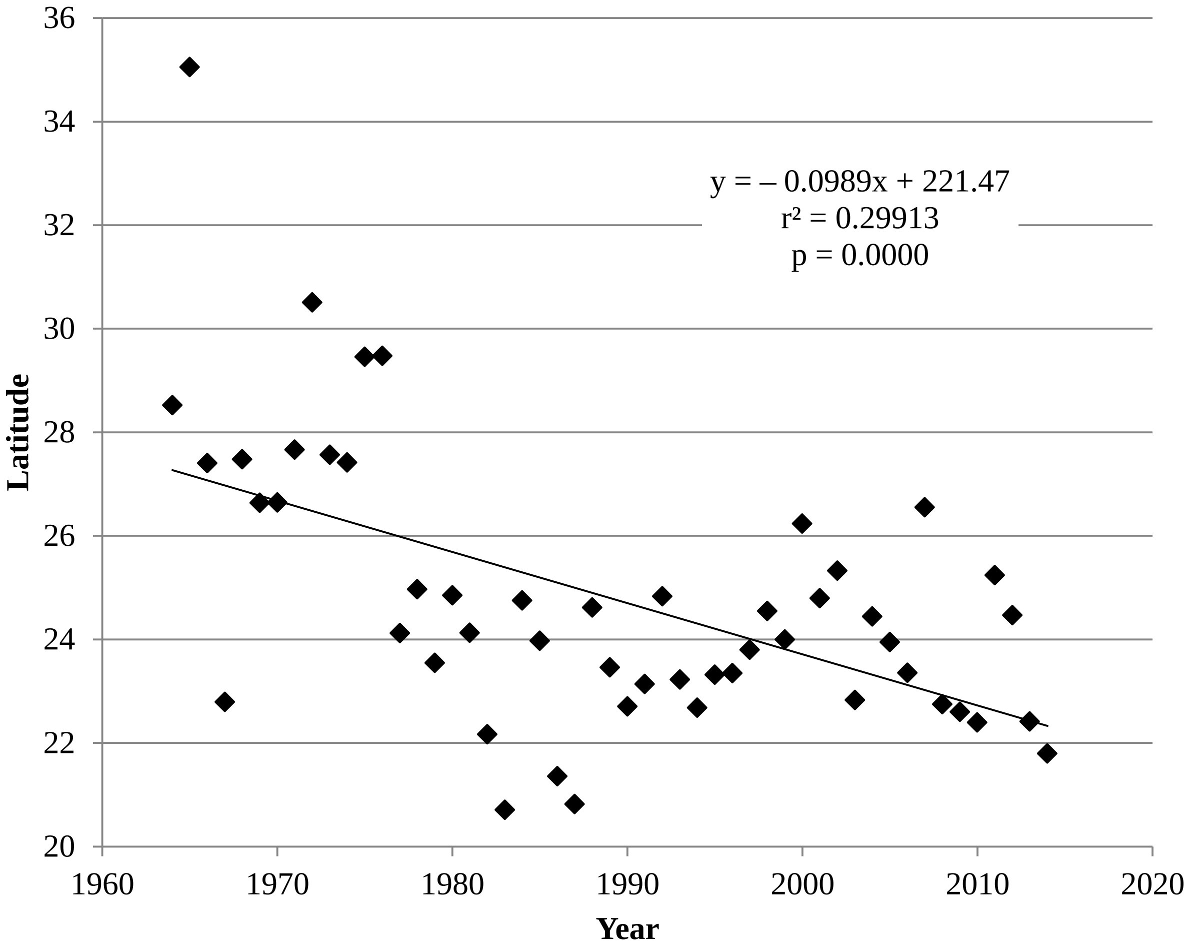

Figure 3a. Mean annual latitude of the LMI of TCs in the North Atlantic and Western Pacific basins.

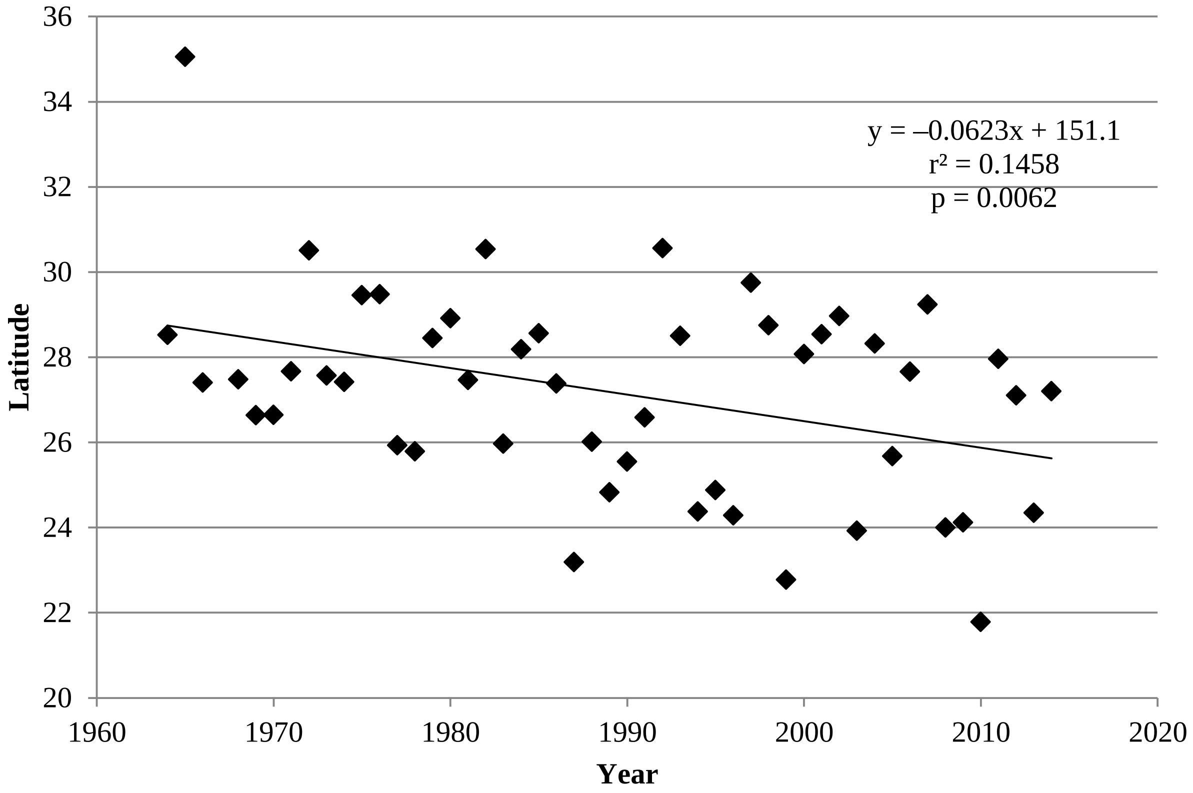

Figure 3b. Mean annual latitude of the LMI of TCs in the North Atlantic basin.

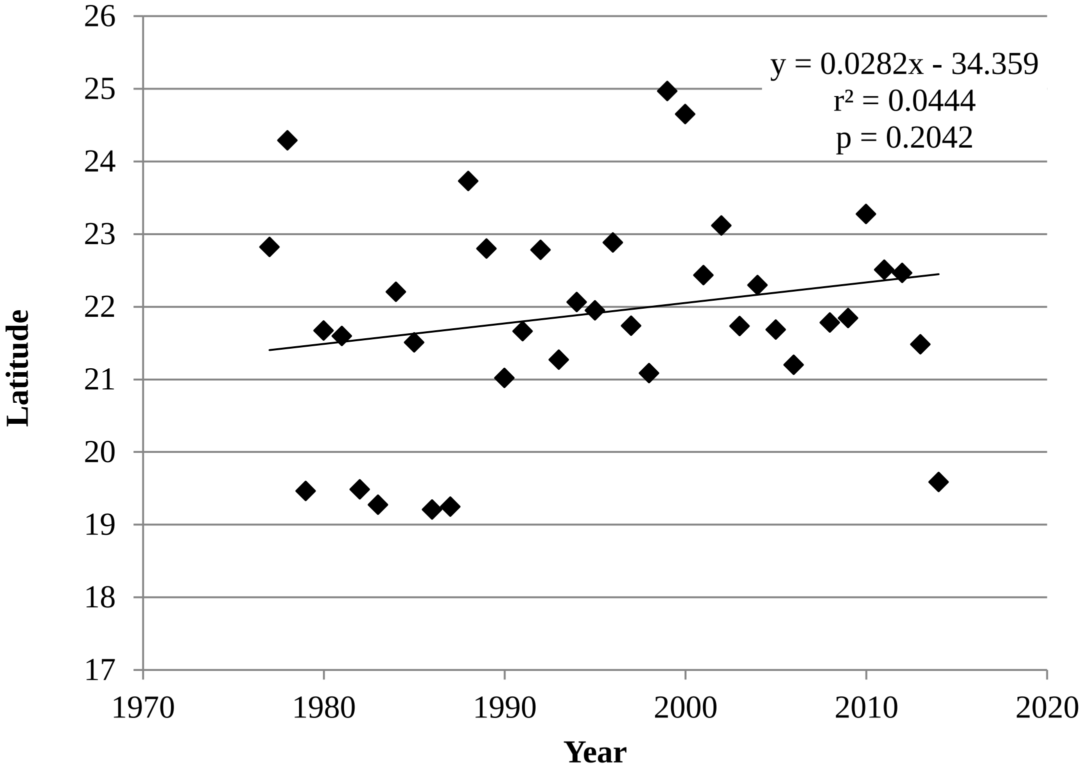

Figure 3c. Mean annual latitude of the LMI of TCs in the Western Pacific basin.

degrees of latitude per decade, and shifted north at a rate of 0.07 ($r^2 = 0.00$) degrees of latitude per decade in the Western Pacific basin. Using a ten-year moving average of the LMI location of hurricanes resulted in a significant ($p < 0.05$) southward shift of 1.5 ($r^2 = 0.87$) degrees of latitude per decade in the North Atlantic basin (Figure 4) and a significant ($p < 0.05$) northward shift of 0.64 ($r^2 = 0.68$) degrees of latitude per decade in the Western Pacific basin (Figure 5). While analyzing the regression of a ten-year moving average infringes upon autocorrelation, I am still interested in the trends found using these methods.

4.2 LMI Shift based on intensity

When hurricanes were broken up into quartiles based on storm intensity (Table 1), I found that the weakest hurricanes in the North Atlantic significantly ($p < 0.05$) reached their LMI the farthest north, while the strongest hurricanes significantly ($p < 0.05$) reached their LMI the farthest south (Figure 6). All quartiles shifted toward the equator, and the top 50% of hurricanes experienced the strongest shift (Figure 6). The hurricanes in quartile 3 significantly ($p < 0.05$) shifted south at a rate of 1.37 ($r^2 = 0.50$) degrees of latitude per decade, and the hurricanes in quartile 4 (the strongest storms) significantly ($p < 0.05$) shifted south at a rate of 1.79 ($r^2 = 0.67$) degrees of latitude per decade. In the Western Pacific basin, I found that typhoons reached their LMI the farthest south while the weakest generally reached their LMI the farthest north. The LMI of the top 50% and bottom 25% of Western Pacific typhoons shifted poleward significantly ($p < 0.05$) over time (Figure 7). The 2nd quartile shifted south at a rate of 0.04 degrees of latitude per decade, but had an extremely low r^2 (0.00). The other three quartiles shifted at similar rates of 0.13 ($r^2 = 0.59$), 0.12 ($r^2 = 0.35$), and 0.13 ($r^2 = 0.73$) degrees latitude per decade, showing a fairly consistent and significant ($p < 0.05$) shift poleward. The top 25% of storms (the strongest storms) observed the most consistent poleward shift ($r^2 = 0.73$).

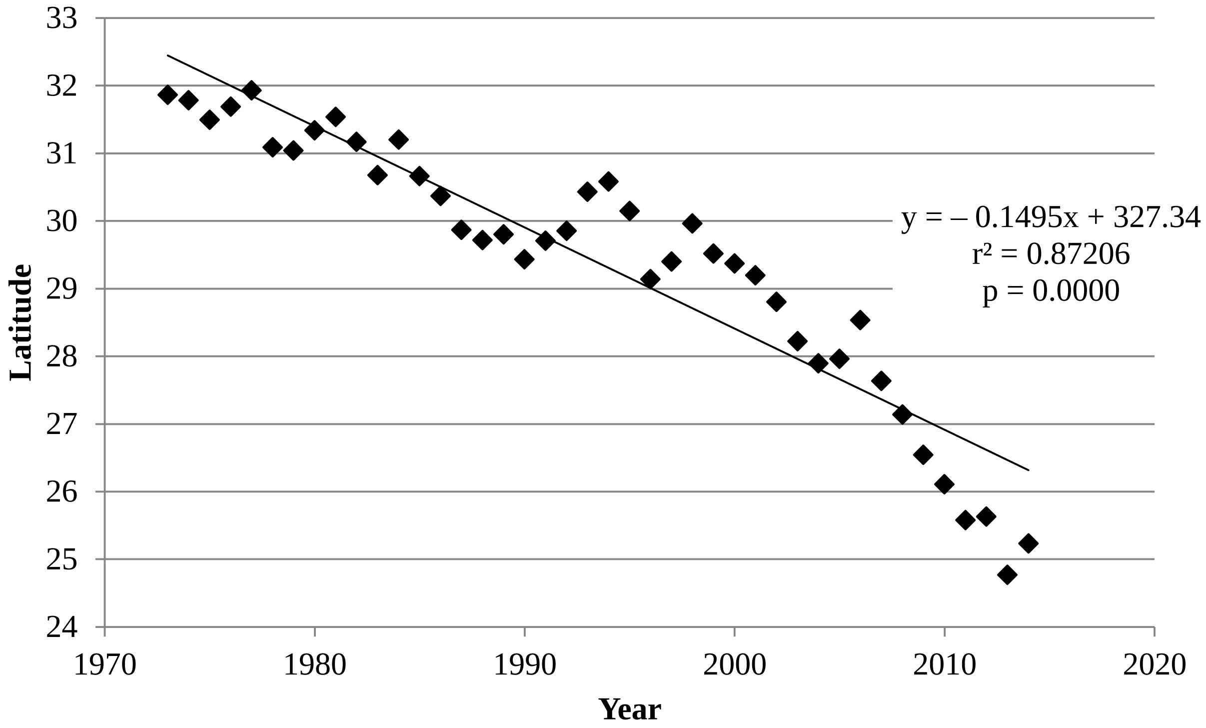

Figure 4. Ten-year moving average of the LMI latitude of hurricanes in the North Atlantic basin. The average value is plotted at the last year of the 10-year time frame, with the first decade being 1964–1973.

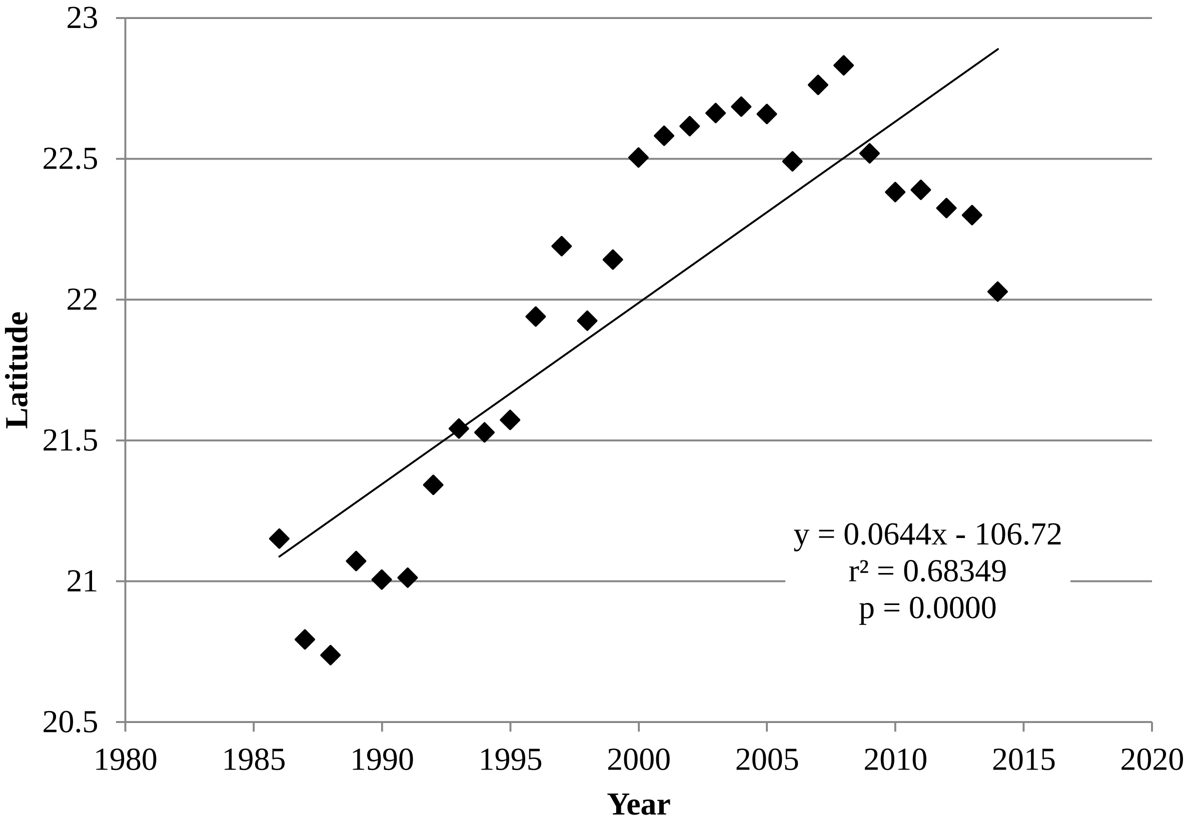

Figure 5. Ten-year moving average of the LMI latitude of typhoons in the Western Pacific basin. The average value is plotted at the last year of the 10-year time frame, with the first decade being 1977–1986.

Table 1. The maximum LMI wind speed (knots), decile category, and n for each quartile for all hurricanes in the North Atlantic and Western Pacific basins.

		North Atlantic	n (NA)	Western Pacific	n (WP)
Quartiles	1	75	121	75	173
	2	85	40	85	121
	3	110	89	100	146
	4	165	70	140	74
Deciles	1	65	40	65	53
	2	70	39	70	65
	3	75	42	75	55
	4	80	23	80	70
	5	85	41	85	51
	6	95	36	90	47
	7	105	29	95	42
	8	115	22	100	57
	9	125	48	105	23
	10	165	30	140	51

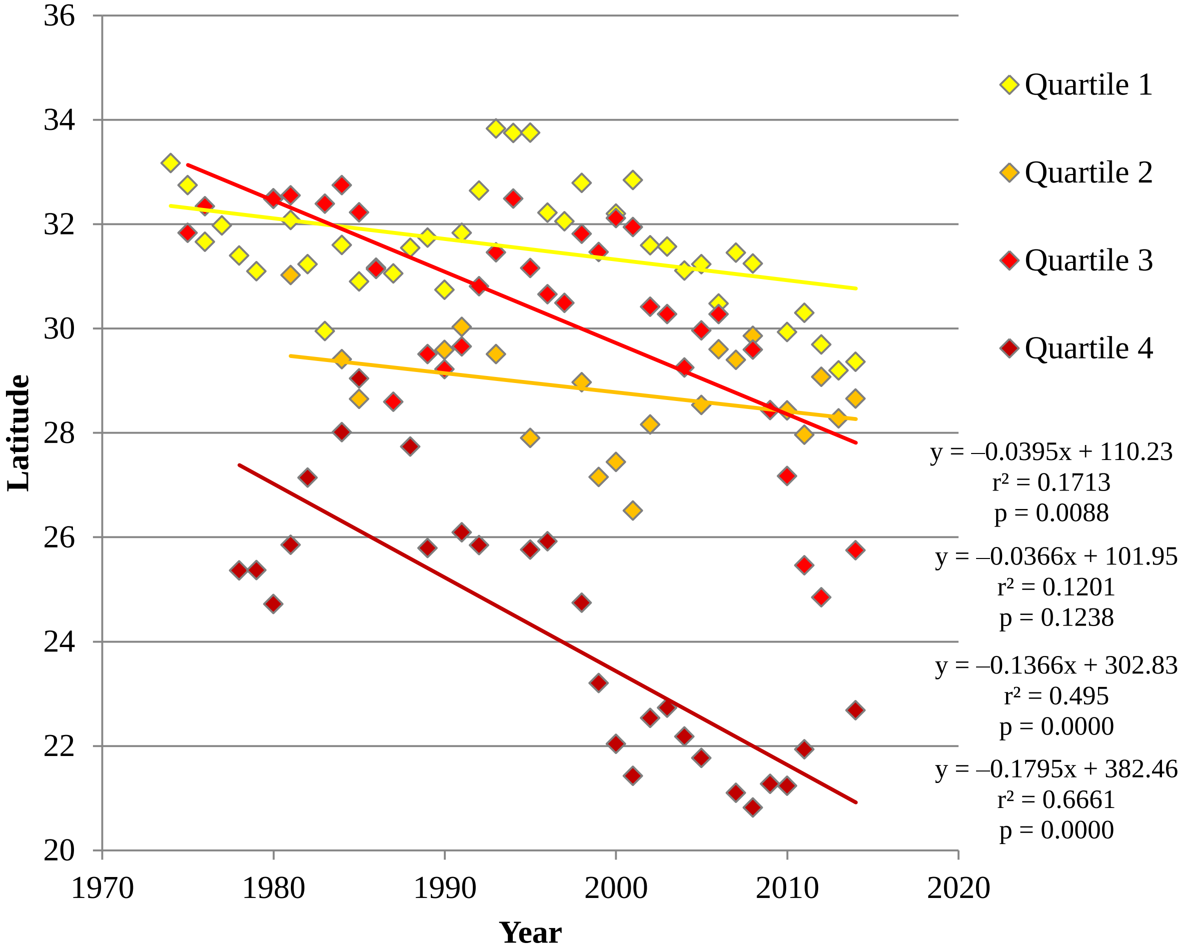

Figure 6. Ten-year moving average of the latitude of the LMI of hurricanes in the North Atlantic basin separated into quartiles based on intensity. The strongest storms are in quartile 4.

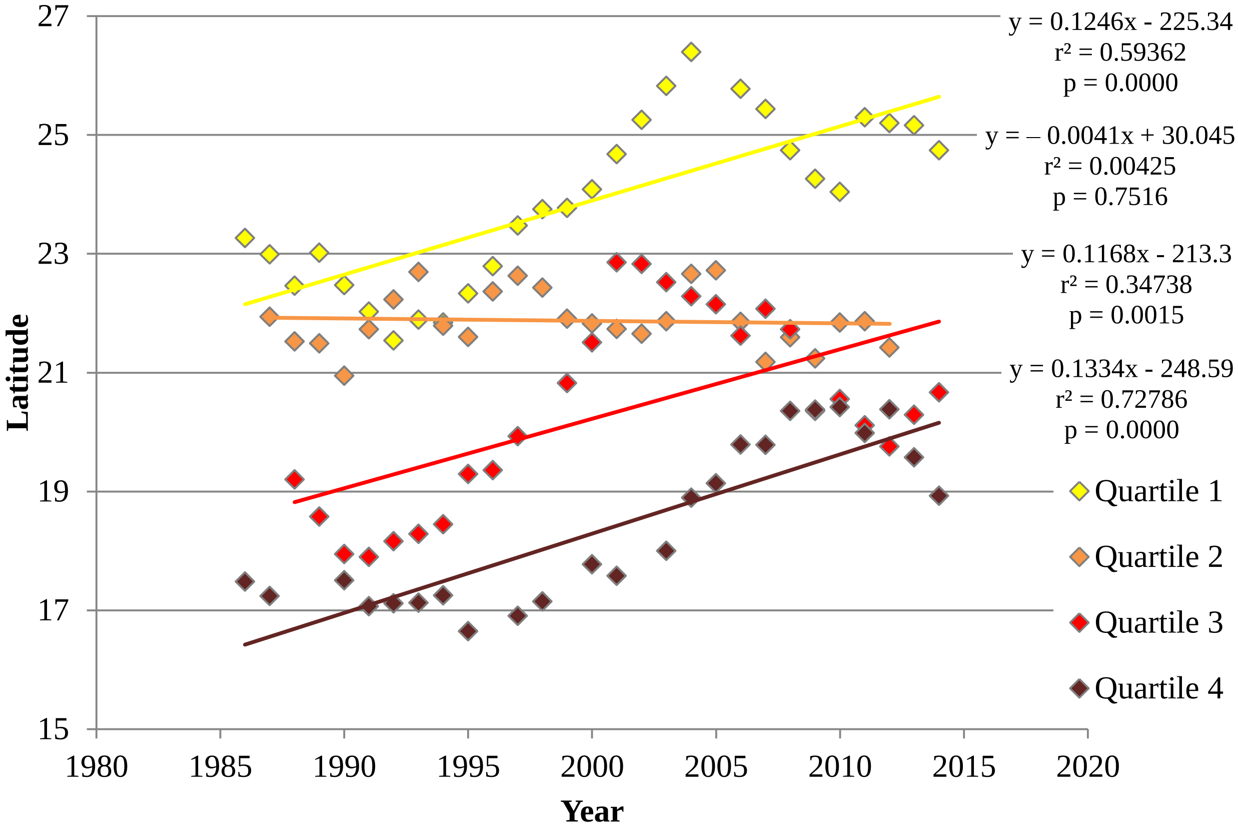

Figure 7. Ten-year moving average of the latitude of the LMI of typhoons in the Western Pacific basin separated into quartiles based on intensity. The strongest storms are in quartile 4.

To further investigate the difference in LMI migration of hurricanes of different strengths, the mean LMI latitude was broken up into deciles based on intensity (Table 1) for the North Atlantic and Western Pacific basins (Table 2). In the North Atlantic, the LMI location of every category except for the 9th decile shifted toward the equator. The LMI location in the 9th decile shifted poleward at a rate of 1.21 ($r^2 = 0.12$) degrees of latitude per decade. In the Western Pacific basin, the LMI of the 9th decile exhibited the greatest significant ($p < 0.05$) shift poleward of 2.71 ($r^2 = 0.81$) degrees of latitude per decade. The LMI location of the weakest storms (bottom 10%) also experienced a significant ($p < 0.05$) poleward shift of 2.08 ($r^2 = 0.52$) degrees of latitude per decade. The strongest storms (top 10%) only shifted poleward at a significant ($p < 0.05$) rate of 0.83 ($r^2 = 0.71$) degrees of latitude per decade.

4.3 Distance from LMI to landfall

All hurricanes combined showed no significant trend in the distance between their LMI and landfall location (Figure 8). Dividing the hurricanes into separate basins increased the r^2 and highlighted the different patterns occurring in each basin. A ten-year moving average was used to smooth out extremes and highlight general trends in the data. The distance from LMI to landfall location increased significantly ($p < 0.05$) in the North Atlantic basin at a rate of 152.03 ($r^2 = 0.57$) kilometers per decade (Figure 9), and decreased significantly ($p < 0.05$) in the Western Pacific basin at a rate of 50.84 ($r^2 = 0.26$) kilometers per decade (Figure 10).

In the North Atlantic basin, all hurricanes reached LMI farther away from landfall (Figure 11). The weakest hurricanes in the North Atlantic basin, contained in quartile 1, reached their LMI farther away from landfall at a rate of 33.62 ($r^2 = 0.03$) kilometers per decade, though the trend is weak and insignificant. The hurricanes in quartile 2 reached their LMI farther away from landfall at a significant ($p < 0.05$) rate of 312.38 ($r^2 = 0.49$) kilometers per decade, with a

Table 2. The slope, r^2, and p-value of a ten-year moving average of the latitude of LMI, separated into deciles based on intensity, for hurricanes in the North Atlantic (NA) and Western Pacific (WP) basins. The strongest storms are in the 10th decile.

Decile	**Slope (NA)**	**r^2 (NA)**	**p-value**	**Slope (WP)**	**r^2 (WP)**	**p-value**
1	-0.02	0.00	0.7909	0.21	0.52	0.0002
2	-0.19	0.73	0.0000	0.07	0.55	0.0002
3	-0.03	0.14	0.0906	0.14	0.41	0.0022
4	-0.01	0.03	0.6047	-0.01	0.02	0.5075
5	-0.05	0.05	0.4632	0.05	0.21	0.0560
6	-0.04	0.05	0.2956	0.07	0.25	0.0329
7	-0.09	0.07	0.1919	-0.08	0.19	0.1593
8	-0.37	0.06	0.2857	0.06	0.14	0.1155
9	0.12	0.12	0.1569	0.27	0.81	0.0009
10	-0.09	0.11	0.1519	0.08	0.71	0.0000

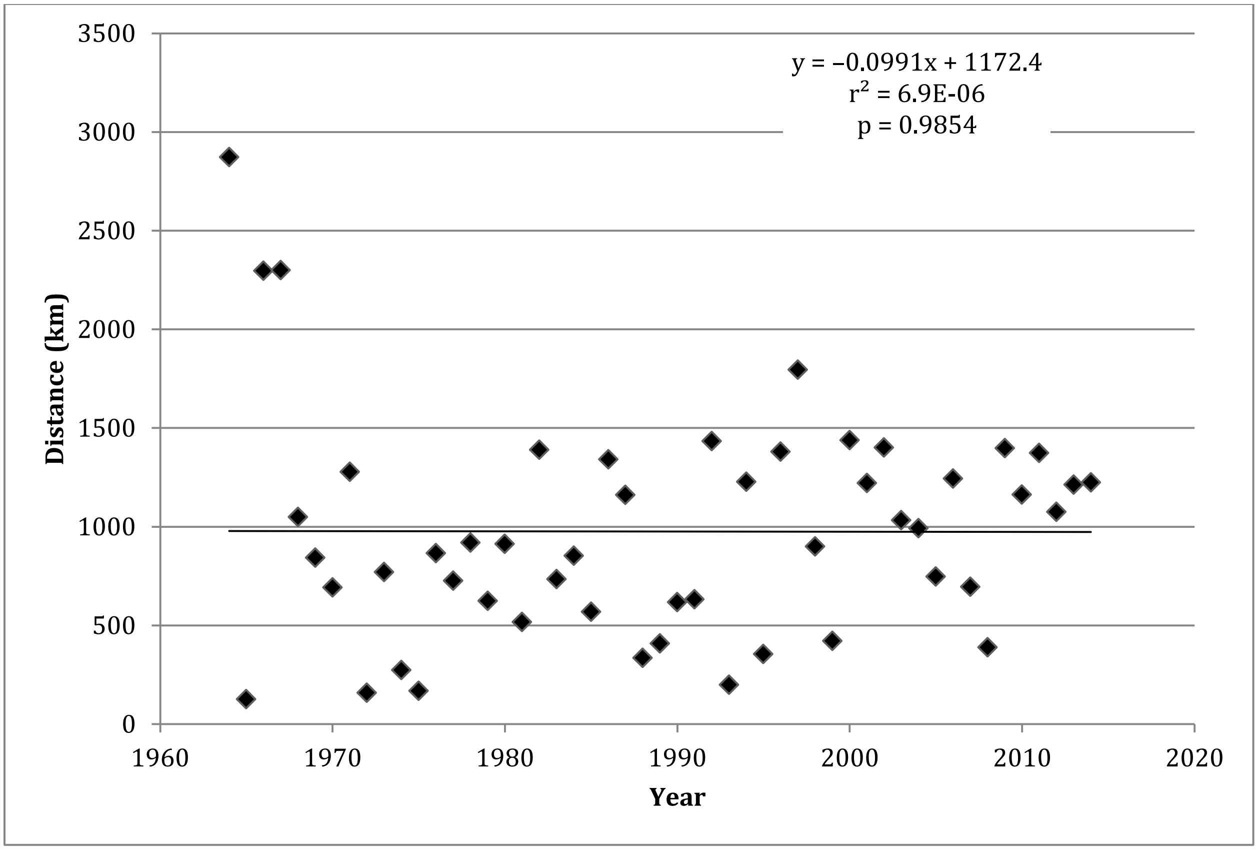

Figure 8. Mean annual distance from LMI to landfall location for hurricanes in the North Atlantic and Western Pacific basins.

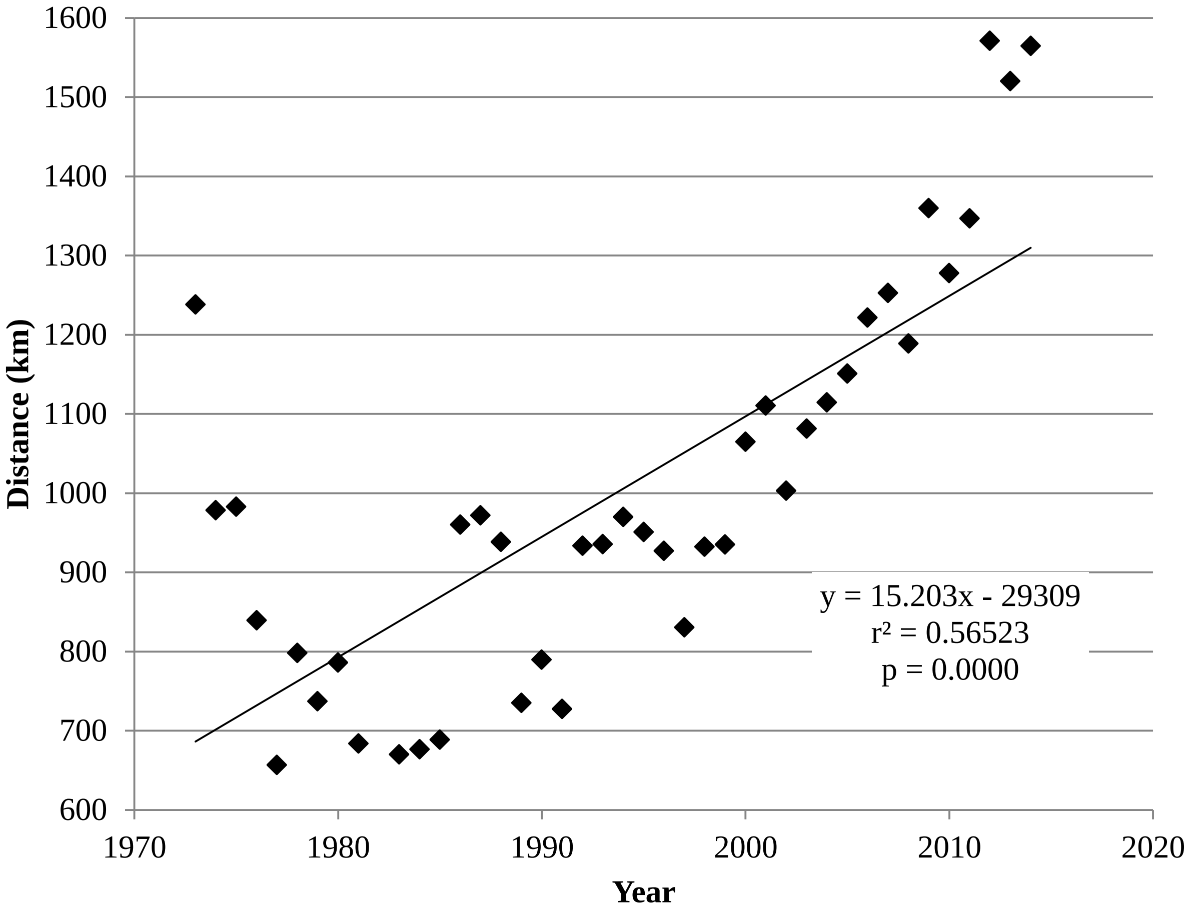

Figure 9. Ten-year moving average of distance from LMI to landfall location for North Atlantic hurricanes. The average value is plotted at the last year of the 10-year time, with the first decade being 1964–1973.

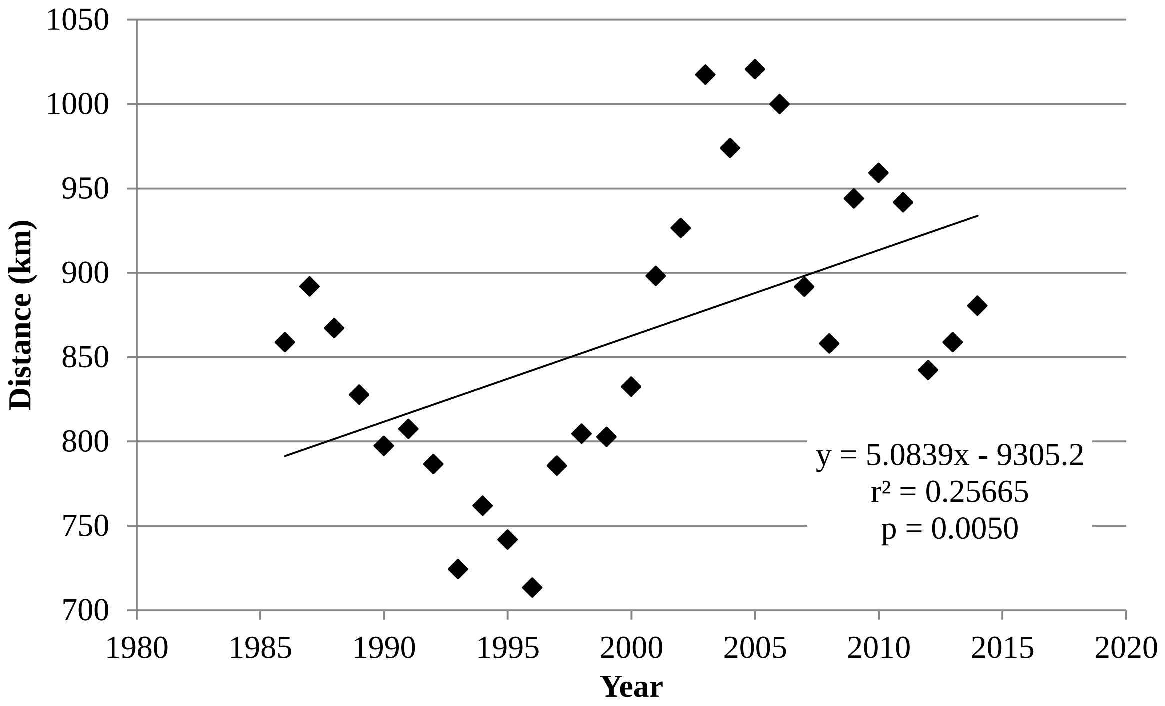

Figure 10. Ten-year moving average of distance from LMI to landfall location for Western Pacific typhoons. The average value is plotted at the last year of the 10-year time frame, with the first decade being 1977–1986.

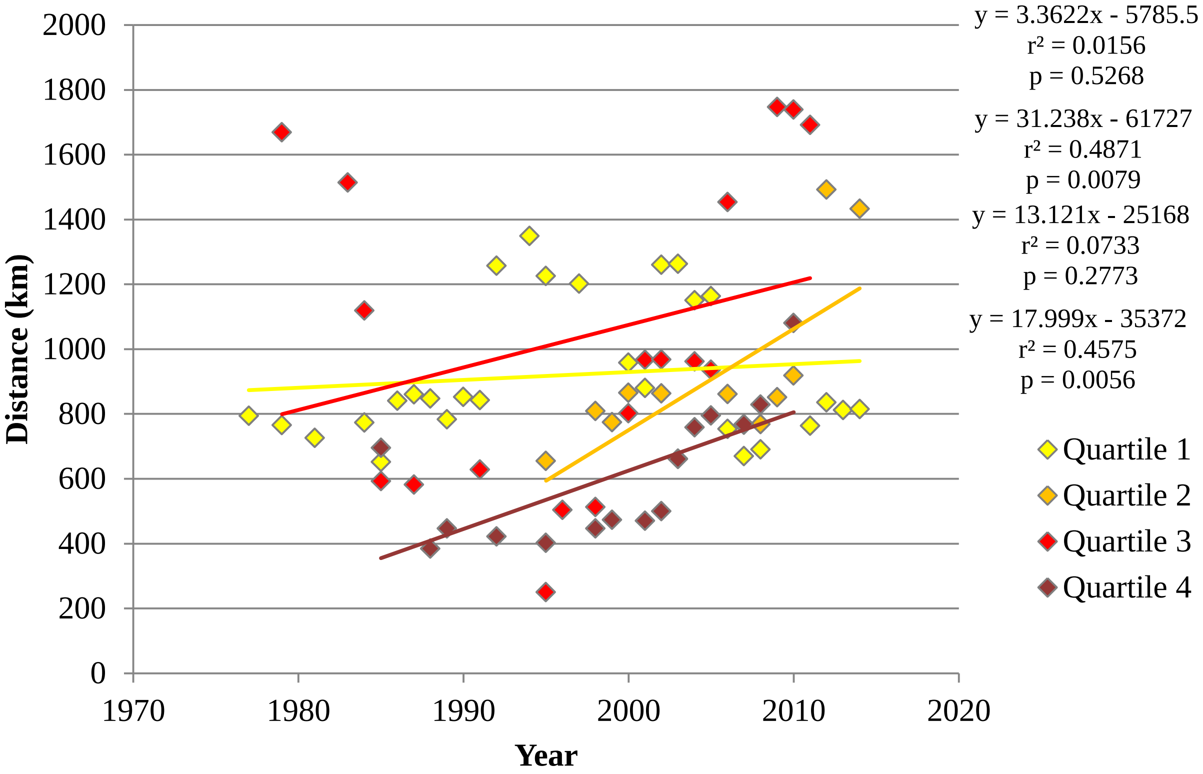

Figure 11. Ten-year moving average of the distance from LMI to landfall location for hurricanes in the North Atlantic basin separated into quartiles based on intensity. The strongest storms are in quartile 4.

much stronger relationship. Hurricanes in quartile 3 reached their LMI farther away from landfall at a rate of 131.2 ($r^2 = 0.07$) kilometers per decade, and hurricanes in quartile 4 reached their LMI significantly ($p < 0.05$) farther away from landfall at a rate of 179.99 ($r^2 = 0.46$) kilometers per decade.

In the Western Pacific basin, the trends of LMI migration for the various intensity levels were not as uniform as in the North Atlantic basin. The top 25% of typhoons reached their LMI closer to landfall, while the bottom 75% of typhoons reached LMI farther away from landfall (Figure 12). The weakest storms in the Western Pacific basin, contained in quartile 1, reached their LMI farther away from landfall at a rate of 36.99 kilometers per decade, though the trend is weak ($r^2 = 0.06$). The typhoons in quartile 2 reached their LMI farther away from landfall at a much faster rate of 232.81 kilometers per decade, with a much stronger, significant ($p < 0.05$) relationship ($r^2 = 0.616$). Similar to quartile 1, typhoons in quartile 3 reached their LMI farther away from landfall at a rate of 38.29 kilometers per decade, with a weak trend ($r^2 = 0.04$). However, the Western Pacific typhoons in quartile 4 reached LMI significantly ($p < 0.05$) closer to landfall at a rate of 132.31 ($r^2 = 0.36$) kilometers per decade.

Next, the distances from LMI to landfall location were separated into quartiles (Table 3) based on intensity for hurricanes in each basin (Table 4) to further explore the trends among various intensities. Again, a ten-year moving average was used. Hurricanes in the North Atlantic basin, when separated into deciles, showed the uniform positive slopes found in the quartile regression may not be an accurate depiction of the trends among intensities. The 3rd, 6th, 8th, and 10th deciles contained hurricanes reaching LMI farther away from landfall, but the 1st, 2nd, 5th, and 7th deciles contained hurricanes reaching LMI closer to landfall. This could also be a

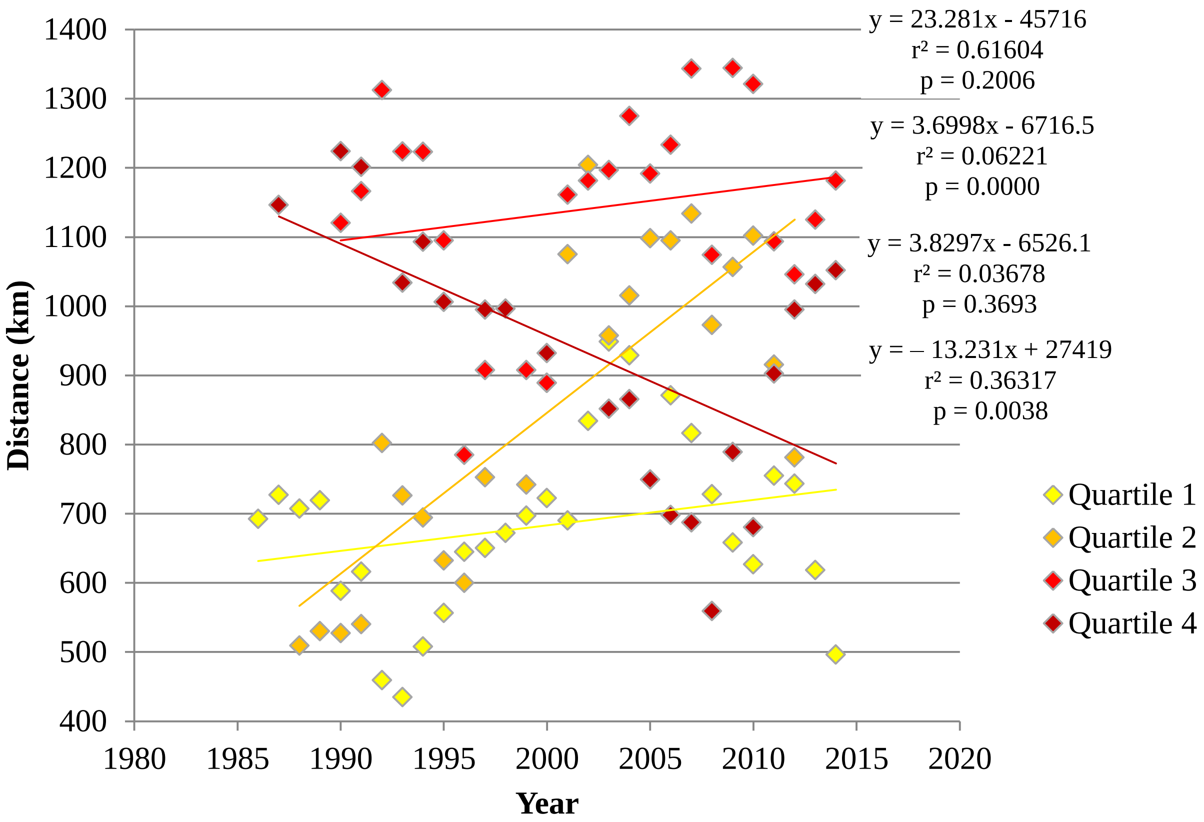

Figure 12. Ten-year moving average of the distance from LMI to landfall location for typhoons in the Western Pacific basin separated into quartiles based on intensity. The strongest storms are in quartile 4.

Table 3. The maximum LMI wind speed (knots), decile category, and n for each quartile for all hurricanes reaching LMI before landfall in the North Atlantic and Western Pacific basins.

	North Atlantic	n (NA)	Western Pacific	n (WP)
Quartile				
1	75	58	75	121
2	90	30	85	89
3	120	42	100	95
4	165	41	140	51
Decile				
1	65	18	65	36
2	70	17	70	44
3	75	23	75	41
4	80	11	80	53
5	90	19	85	36
6	105	21	90	24
7	115	14	95	28
8	125	20	100	43
9	139	11	110	37
10	165	17	140	14

Table 4. The slope, r^2, and p-value of a ten-year moving average of the change in distance from LMI to landfall location for the North Atlantic (NA) and Western Pacific (WP) basins. Hurricanes are separated into deciles based on intensity. The strongest storms are in the 10th decile.

Decile	**Slope (NA)**	**r^2 (NA)**	**p-value**	**Slope (WP)**	**r^2 (WP)**	**p-value**
1	-14.08	0.70	0.0381	0.02	0.00	0.9978
2	-37.27	0.73	0.0144	15.86	0.56	0.0005
3	28.54	0.75	0.0006	11.61	0.32	0.0341
4	*			26.74	0.59	0.0001
5	-16.32	0.79	0.0451	25.59	0.57	0.0031
6	14.98	0.15	0.3480	7.12	0.03	0.6984
7	-20.66	0.83	0.0919	34.90	0.56	0.0132
8	13.24	0.04	0.8027	-4.07	0.01	0.6911
9	*			0.99	0.00	0.8241
10	52.63	0.84	0.0810	-42.46	0.77	0.3167

* Years with too few storms to create a ten-year moving average

result of the smaller sample size once the storms were separated into deciles.

Consistent with the results found in quartile regression, the strongest 10% of typhoons in the Western Pacific basin reached their LMI closer to landfall at a rate of 424.62 ($r^2 = 0.77$) kilometers per decade. The 8th decile also reached their LMI closer to landfall but at a slower rate of 40.74 ($r^2 = 0.01$) kilometers per decade and with a weak relationship. Typhoons of all other deciles in the Western Pacific basin reached their LMI farther away from landfall. Typhoons in the 7th decile reached their LMI farther away from landfall at the fastest rate of 349.06 ($r^2 = 0.56$) kilometers per decade.

CHAPTER FIVE

DISCUSSION

5.1 Latitudinal Shift of LMI

Globally, all Northern Hemisphere TCs reached their LMI farther south over the period; however, much of this global southward shift could be a result of the missing years from 1964–1976 in the Western Pacific dataset. The inclusion of the Western Pacific LMI beginning in the year 1977 brings the average latitude farther south because LMI is generally reached at lower latitudes in the Western Pacific basin than in the North Atlantic basin. Therefore, I found that assessing LMI migration by basin was more useful. The annual averages for each basin showed TCs in the Western Pacific basin reached their LMI at increasingly higher latitudes over the past 38 years, and TCs in the North Atlantic basin reached their LMI at increasingly lower latitudes over the past 51 years. These shifts in LMI occurred at different rates in the North Atlantic and Western Pacific basins. The LMI shifted south in the North Atlantic basin twice as fast as it shifted north in the Western Pacific basin. For stronger storms, the southern shift strengthened in the North Atlantic basin and the northern shift weakened in the Western Pacific basin. These results suggest stronger hurricanes moved farther south in the North Atlantic basin and the weaker storms moved farther north in the Western Pacific basin. This latitudinal shift based on intensity highlights an additional difference between the two basins and demonstrates the need to further assess the differences among storm intensities.

A possible explanation for the different LMI migration patterns in the two basins is the point of recurvature of a TC path. Recurvature of a TC path signals an internal change in the storm and gives forecasters insight to the future intensity of the storm. Weaker storms often reach LMI during recurvature, and stronger storms reach LMI before recurvature (Evans and

McKinley 1998). Two-thirds of TCs in the Western Pacific reached their LMI during recurvature compared to only 25% of TCs in the North Atlantic basin reaching LMI during recurvature (Evans and McKinley 1998). While this could be because of intensity differences, another explanation for this difference is that many North Atlantic TCs intercept landfall before completing their natural recurvature path. In the North Atlantic basin, 26% of all recurving storm paths intercepted land before recurvature compared to 12% of recurving paths in the Western Pacific (Evans and McKinley 1998). Because landfall diminishes the intensity of a storm, this higher percentage of TCs in the North Atlantic basin landfalling before recurvature could affect the percentage of storms continuing to strengthen over warm water.

Assessing the migration of the LMI using a ten-year moving average of LMI latitude increased the r^2 values in both basins because it muted any fluctuations that may have been caused by particular climate patterns or unusual storms, as well as autocorrelation. Data are cyclically modified by inter-annual oscillations, such as NAO or ENSO, which affect TC tracks, frequencies, and intensities. An abnormal storm can also skew an annual average. One such extreme storm, tropical storm Keith, was a Category 1 hurricane in the North Atlantic basin that reached LMI around 52° N. While the average Category 1 storm in the North Atlantic basin reached their LMI at 31° N, just north of the Florida border, Keith reached its LMI around Newfoundland. Because my study was interested in overall trends and not extreme storms or extreme years, the decadal mean presents a more fitting representation than the annual mean.

5.2 LMI Shift based on intensity

After achieving different results by including or removing weaker TCs in the regression, I investigated the relationship between intensity and the shift in LMI location. The hurricanes were separated by intensities using both quartiles and deciles, and the analyses were repeated for both basins. The findings suggest the shift in LMI latitude varies by intensity in both basins. In the North Atlantic basin, all hurricanes reached their LMI farther south, showing this southward trend is consistent. However, the strongest North Atlantic hurricanes reached LMI farther south at a faster rate than the weaker hurricanes. Similarly, the strongest Western Pacific typhoons reached LMI the farthest south, but they also saw the largest northward shift of all other intensity values.

A few mechanisms can explain why the strongest storms experience different LMI migration trends than their weaker counterparts. First, the local ambient environmental conditions farther north are not conducive to the formation of strong (top 25% of intensity) hurricanes. If cyclogenesis occurs farther north, a hurricane may never have the opportunity to strengthen to a high intensity. The trend in the strongest storms could also be related to the recurvature of storm tracks. In the North Atlantic basin, weaker storms generally reach their LMI the farthest north, and they also reach LMI during recurvature (Evans and McKinley 1998). If so many hurricanes in the North Atlantic are reaching landfall before they recurve, this could explain why storms are not intensifying farther north in the North Atlantic basin.

The influence of the NAO may contribute to trends in North Atlantic LMI latitude. TCs in the North Atlantic basin intersect land because of the influence of the NAO, cutting short the potential intensification of the storm. An excited stage of the NAO steers TCs toward the east coast, because the TCs recurve at higher latitudes (Elsner et al. 2000). Likewise, a relaxed stage of the NAO steers TCs toward the Gulf Coast because TCs recurve at lower latitudes (Elsner et al. 2000). Interestingly, a positive phase of the NAO is associated with above-average SST in the northern North Atlantic basin (Elsner et al 2000). Therefore, an excited stage both steers TC tracks farther north and has warmer SSTs up north, perhaps allowing storms to intensify as they travel farther north. Because of the strong influence of the NAO, LMI latitude in the North Atlantic basin has the potential to oscillate with NAO phases. Also, if many of the years in the dataset experienced a relaxed stage of the NAO, stronger storms would have likely intersected landfall farther south, never getting an opportunity to intensify farther north. One or several of these hypotheses may explain why the strongest hurricanes reach LMI the farthest south.

The patterns of LMI migration in relation to intensity in the North Atlantic basin confirm from previous studies that suggest the strongest hurricanes reach their LMI farthest south, and that they are reaching their LMI increasingly southward. Meanwhile, Elsner et al. (2008) found the strongest storms in the North Atlantic basin were increasing in intensity. These two trends may be related. If the strongest storms are staying farther south, they are spending more time in favorable conditions allowing them to intensify.

In the Western Pacific basin, most typhoons are reaching their LMI farther north. Only one intensity category shifted south, but the trend was weak. While the weakest typhoons reached LMI the farthest north in the Western Pacific basin, the strongest 25% of typhoons shifted north the most consistently. This could be because the environment needed to create strong typhoons is shifting north as well. The strongest typhoons in the Western Pacific basin shifted north at a faster rate than any other strength storm. Because Western Pacific typhoons reached LMI farther south than any other category and are shifting north faster than any other category, this could potentially result in a clustering of LMI at a certain range of latitudes. This clustering of typhoons may shrink the impacted area, but it may also increase the effect felt in these areas.

Elsner et al. (2008) found that the strongest TCs are getting stronger in the Western Pacific basin, but at a slower rate than the North Atlantic. This study found the strongest typhoons are moving north the fastest in the Western Pacific basin. If this trend continues, this could have serious ramifications in the Western Pacific basin. The intensification of the strongest TCs may result in damaging TCs striking communities unprepared for such intense storms. If these TCs reach higher levels of intensity in the higher latitudes, this widens the threat area for intense TCs. Additionally, it is possible that the increase in intensity of the strongest typhoons in the West Pacific is hindered by the migration northward into a less ideal environment.

The removal of the weakest Western Pacific storms (i.e., less than typhoon intensity) caused a decrease in the significance of the change in annual mean LMI location. Therefore, while the strongest typhoons are showing the largest LMI migration patterns and have the greatest effect on humans, the weakest TCs are also migrating.

5.3 Distance from LMI to landfall

While the shift of the LMI location north or south may have serious implications for coastal communities, another crucial concern is the change in distance from LMI to landfall location. The distance between LMI and landfall location was calculated for every hurricane that made landfall after achieving their LMI, and was separated by intensities using both deciles and quartiles. The LMI in both the North Atlantic and Western Pacific basins was generally being reached farther away from landfall over time. However, a few intensity levels deviated from this general trend.

In the North Atlantic basin, hurricanes in all quartiles consistently reached LMI farther away from landfall. This uniformity resembles the shift toward the equator of all LMI quartiles in the North Atlantic basin. The deciles in the North Atlantic basin lack this uniformity, with four deciles shifting closer to landfall and four shifting farther away from landfall. This is likely because of the small sample size of each decile after calculating the ten-year moving averages.

The overall shift of LMI farther away from landfall should come as a relief to coastal communities in the North Atlantic basin. The top 10% of the strongest hurricanes reached their LMI farther away from landfall each year than any other decile. If this trend continues, storms should have more time to lessen in intensity before intersecting a coastal community. While a TC making landfall may still have disastrous effects, it will not have as large of an effect as it may have at maximum intensity. This consistency of North Atlantic hurricanes to reach their LMI closer to the equator and farther away from landfall may benefit the United States. If these trends continue, the strongest part of a hurricane will continue moving farther away from the U.S. coastline. A hurricane reaching its LMI farther south and farther away from the coast poses a lesser threat than a hurricane reaching LMI closer to landfall and farther north.

In the Western Pacific basin, the weakest 75% of typhoons reached their LMI farther away from landfall while the top 25% reached their LMI closer to landfall. Breaking down intensity into deciles confirmed the anomaly of only the strongest typhoons reaching their LMI closer to landfall. The strongest typhoons in the Western Pacific basin reached their LMI both closer to landfall and farther north than any other intensity category. This strong, consistent shift of LMI toward landfall presents a threat to the coastal communities in the Western Pacific basin. Paired with the northern shift of LMI, this tendency of stronger typhoons to reach their LMI closer to landfall threatens communities farther north. These unsuspecting communities may experience an increase in the frequency and strength of TCs. If this trend continues, the strongest TCs may make landfall at coastal locations unprepared for the intense winds, heavy rains, and storm surges accompanying TCs. Lastly, previous research discovered the strongest 10% of Western Pacific TCs are increasing in intensity at a rate of 0.14 m s^{-1} yr^{-1} (Elsner et al. 2008).

The combination of typhoons reaching LMI farther north, closer to landfall, and at a higher intensity puts the Western Pacific basin in a dangerous situation.

One potential explanation for the different trends regarding the distance from LMI to landfall location in the two basins is a difference in SST. Elsner et al. (2008) hypothesized the increase in TC intensity was related to the increase in SST, because warmer oceans can contribute more heat and therefore energy to TCs. A small positive correlation was found in every ocean basin between the increase in SST and the increase in LMI of the strongest storms (Elsner et al. 2008). SST is also correlated to PDI in the North Atlantic and North Pacific basins since 1975 (Emanuel 2005). Emanuel (2005) hypothesized the increase in both SST and PDI is related to anthropogenic activity. However, previous research suggests the weakening of storms closer to the poles is based on angular momentum conservation and not environmental flow or SST (Riehl 1972; Evans and McKinley 1998). So, while SST affects TC intensity, there may be a latitudinal limit may exist for influence by SST.

The largest TCs have been known to modify their environment rather than being modified by it (Evans and McKinley 1998). This may help explain the divergence of the strongest TCs from the other intensities. While all other typhoons in the Western Pacific basin are reaching LMI farther away from landfall, the strongest are reaching their LMI closer to landfall. The strongest TCs may affect the environment around them rather than being affected, thereby intensifying longer than storms of other intensities. This could also aid the strongest storms reaching farther north at the fastest rate in the Western Pacific basin. If these strong storms are not as weakened by their environment, they have a greater chance of traveling farther north.

These findings reinforce the importance of the study of extremes in climatology. Previous research has shown that means in precipitation (Turner and Slingo 2009) and temperature (Kürbis et al. 2009) may not show a notable trend, while the extremes may be changing significantly. Similarly, the average trends alone communicate little about the changing nature of TC climatology, but an analysis of the extreme storms shows the potential danger or potential benefit of changing TC intensity trends.

CHAPTER SIX

CONCLUSION

This study assesses the recent (1964–2014) spatial changes in the LMI of TCs in relation to TC intensity and landfall location in the North Atlantic and Western Pacific basins. This objective was achieved by analyzing changes in both latitude of LMI and distance from LMI to landfall location over time. The latitude that TCs reached LMI was calculated using the IBTrACS dataset in ArcGIS and was analyzed over time for each basin using linear regression. The data were also broken down by intensity into quartiles and deciles and analyzed using quantile regression. The same process was repeated for the distance from LMI from landfall location.

The findings indicated LMI migration trends differed largely by basin and by intensity. In the North Atlantic basin, all hurricanes are reaching their LMI closer to the equator over time, and the strongest hurricanes are consistently reaching their LMI the farthest south. Hurricanes are also reaching LMI farther away from landfall over time, and the strongest are reaching LMI farther away from landfall at the fastest rate. In the Western Pacific basin, typhoons are reaching LMI farther north over time, and the LMI of the strongest typhoons is shifting north at the fastest rate. Typhoons are also reaching LMI closer to landfall in the Western Pacific basin, and the LMI of the strongest storms is shifting closer to landfall at the fastest rate.

The results of this study bring a mixture of favorable and adverse effects to the North Atlantic basin. Fortunately, hurricanes are reaching their LMI farther away from landfall in the North Atlantic basin, suggesting these TCs may have a greater opportunity to lower in intensity before landfall. Hurricanes in the North Atlantic basin are reaching their LMI farther south, and the LMI of the strongest TCs are shifting south at the fastest rate. While this southerly trend would be beneficial to the United States, this may bring TCs at a higher intensity and higher frequency to locations south of the United States. A continuation of these trends would bring welcome relief to the United States, but could have negative consequences for Caribbean and Central American countries.

LMI migration in the Western Pacific basin varies greatly based on intensity, but the trends are not as favorable as in the North Atlantic. Typhoons are reaching their LMI farther north in the Western Pacific basin, and the strongest storms are traveling north the fastest. Because the strongest storms reach LMI the farthest south and are shifting north the fastest, this could potentially result in a clustering of LMI at a certain range of latitudes. While this clustering may shrink the impacted area, it may also increase the effect felt in these areas. Typhoons also reach LMI closer to landfall than in the past, and the strongest LMIs are shifting closer to landfall the fastest. This shortens the time in which a TC weakens before making landfall, potentially raising the intensity of landfalling TCs.

This work expands upon previous research that discovered the increasing intensity of TCs (Elsner et al. 2008) and the migration of LMI potentially due to expansion of the tropics (Kossin et al. 2014). The results confirm the previous finding that the strongest storms may experience a different trend or more intense trends than other intensity levels (Elsner et al. 2008). The results of this study are in agreement with the LMI migration patterns detailed in Kossin et al. (2014), but they are not able to support or oppose the expansion of the tropics because the shift of LMI location was inconsistent across the different basins.

A potential weakness in this study is the light consideration of TCs below hurricane strength. While this study focused mainly on the strongest storms, analysis of trends in weaker storms may provide a more robust picture of LMI location trends throughout all intensities.

Another weakness is the lack of consideration of TCs that either reached their LMI inland or over the ocean after making landfall previously. While these did not fit into the scope of this study, these storms may yet provide insight on other interesting research questions, such as the average intensity a storm may reach even after making landfall. Finally, analyzing given datasets using different types of regression other than linear would have added different perspectives on relationships between the variables.

A potential future addition to this study would be the inclusion of the Eastern Pacific Ocean and North Indian Ocean basins, thereby extending analysis to the entire northern hemisphere. This may provide more insight into global LMI location trends as opposed to basin-specific changes. This would enlarge the sample size and the geographical reach of this study. Also, because the border of the tropics fluctuates with the seasons, it may be interesting to assess the LMI location separately by time of year. A relationship may exist between the fluctuation of the tropics and the average LMI location during different parts of the hurricane season. Storms may reach LMI significantly farther north in a certain season than other times of the year. Finally, some of the figures shown in this work appear to demonstrate cyclical patterns in the dataset, perhaps related to oscillations such as NAO or ENSO. I would be interested in doing a multivariate regression, taking into account various oscillations and analyzing their role in LMI trends. Accounting for these cyclical patterns could further delineate how LMI location is migrating over time, potentially as a result of a warming climate.

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VITA

Sarah Bleakney is from Brentwood, Tennessee, and is the youngest of three siblings. She graduated from Ravenwood High School in 2011 and earned her Bachelor of Arts degree in Geography from the University of Tennessee, Knoxville, in 2014. While attending the University of Tennessee, she joined an international geographic honor society, Gamma Theta Upsilon. She was a NOAA Hollings Scholar and completed her summer internship at the National Weather Service in Buffalo, New York, in 2014. She also served an internship at Oak Ridge National Laboratory in the Climate Change Science Institute. She then decided to pursue a Master of Science in Geography with a focus in climatology at the University of Tennessee, Knoxville, under Dr. Kelsey Ellis. She served as a teaching assistant for human geography, physical geography, and GIS courses. While earning her masters, she worked on various research projects focused on the climatology of hazards, such as tornado climatology and hurricane climatology. Her thesis, presented for the Master of Science degree, focused on hurricane climatology.