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Spatial and Temporal Trends in the Location of the Lifetime Maximum Intensity of Tropical Cyclones

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Received: 31 August 2017; Accepted: 5 October 2017; Published: 10 October 2017

Abstract: 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. This study further assessed the recent (1977–2015) spatial changes in the LMI of tropical cyclones, specifically those of tropical storm strength or stronger in the North Atlantic and northern West Pacific basins. Analyses of moving decadal means suggested that LMI locations migrated south in the North Atlantic and north in the West Pacific. In addition to a linear trend, there is a cyclical migration of LMI that is especially apparent in the West Pacific. Relationships between LMI migration and intensity were explored, as well as LMI location relative to landfall. The southerly trend of LMI in the North Atlantic was most prevalent in the strongest storms, resulting in these storms reaching their LMI farther from land. The relationship between intensity and LMI migration in the West Pacific was not as clear, but the most intense storms have been reaching LMI closer to their eventual landfall location. This work adds to those emphasizing the importance of understanding the climatology of the most intense hurricanes and shows there are potential human impacts resulting from any migration of LMI.

Keywords: hurricane; maximum intensity; wind speed; climate change

1. Introduction

Hurricanes are the costliest natural catastrophe in the United States [1,2]. Understanding the future of hurricanes and their destructive power is important to prepare coastlines and mitigate future losses. Hurricane climatologists are interested in long-term variability in tropical cyclone (TC) characteristics such as storm frequency, intensity, track, genesis location, and duration [3,4]. These characteristics vary naturally over time based on large-scale climatic oscillations [3] and, in recent decades, because of the warming of the global climate [5,6].

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 sea surface temperature (SST); however, it is argued that the TC data are not reliable enough to support this claim [5], and dynamical modeling of local conditions is required to fully understand the relationship [7]. Intensity trends are more certain. Reference [5] found TCs have gotten 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 the trend was seen globally. This is consistent with the hypothesis that as the ocean water warms, more energy is available to fuel TC winds. Reference [5] found the median value of the lifetime maximum intensity (LMI) of a TC has not seen any change from 1981–2006. The largest increase in intensity was seen in the 9th decile. As a result, the average number of strong cyclones rose from 13 to 17 in that period, related to an increase in SST of 1 °C [5]. Therefore, while overall frequency trends are not clear, the frequency of the strongest storms has increased.

Spatial changes in intensity have also been identified. One way to view these changes is by assessing the location where TCs are reaching their LMI. Reference [6] analyzed a 31-year span from 1982 to 2012 and discovered the mean annual LMI of TCs has recently been migrating poleward. This trend was consistent across hemispheres, with slight variations in the amount of movement in each basin. LMI in the northern West Pacific had the strongest poleward trend, and there was no significant trend in the North Atlantic basin. Globally, the average poleward shift is 53–62 km per decade, which corresponds to approximately 1° latitude per decade [6]. This trend could potentially be linked to the poleward expansion of the tropics, which are believed to be shifting toward the poles at the same rate (about 1° latitude per decade [8]). As a result, the region most compatible for TC development is also moving poleward [6].

The recent work by [6] called for future studies to examine the poleward shift of LMI and its relationship to tropical expansion for several reasons. First, this shift may alter precipitation totals in affected regions—some areas may experience drier conditions, while others may experience unexpected flooding [9,10]. Further, TCs may strike communities not structurally prepared for the natural disaster [11]. Increases in coastal community hazard exposure and mortality risk from TCs are expected [11] because of the predicted changes in TC frequency and intensity.

We build on the work of [6] to assess the recent spatial changes in LMI in relation to TC intensity and landfall location. We focus on TCs occurring in two active basins: the North Atlantic and the northern West Pacific (hereafter West Pacific). The North Atlantic basin experiences 11% of global TC activity, and over half of these TCs mature into hurricanes [12], with the most active period falling from August to October [13]. The West Pacific basin experiences 32% of global TC activity, making it the most active ocean basin [14]. The official West Pacific typhoon season spans from May to October, with the most active period falling from July to September [14,15]; however, TCs can occur at any time during the year in this basin.

The objective of this study is to assess the recent (1977–2015) spatial changes in the LMI of TCs in relation to TC intensity and landfall location in the North Atlantic and West Pacific basins. This objective is achieved by addressing two main research questions:

1. As the LMI latitude of TCs shifts in the North Atlantic and West Pacific basins, do variations exist in the rate of change for TCs of different intensities? Specifically, because the strongest TCs are demonstrating the largest change in intensities, do the strongest TCs also see the largest latitudinal shift in LMI position? The most intense hurricanes cause the largest proportion of TC-related damage, and it is imperative to understand the spatial and temporal patterns and trends in their intensities.
2. With the shifts in the latitude of LMI, is LMI of the strongest TCs occurring closer to the coastline? This study is the first to analyze LMI migration relative to landfall location.

2. Data and Methods

2.1. Tropical Cyclone 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 [16]. This historic global "best track" dataset contains information on location, intensity, duration, size, and more [16]. Location data are available in 6-hour increments for TCs around the world beginning with the year 1851 in the North Atlantic basin and 1884 in the West Pacific basin. The TC data in IBTrACS are obtained from various sources, including meteorology departments in China, Japan, Australia, and France [16]. IBTrACS combines TC data from around the world into a single website and offers the data in multiple formats.

Frequency and intensity errors are known to exist in the hurricane database [16]. 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. The invention of weather satellites in the 1960s greatly improved the detection and tracking of TCs by using visible and infrared sensors [17]. Regardless of these inherent errors in the data, they are widely used in hurricane climatology research, and when used carefully, are a powerful tool for understanding past hurricane activity.

This study uses TCs spanning 1977 to 2015 for the two most active hurricane basins: the North Atlantic and West Pacific basins (Figure 1). We selected the most recent year available at the time of data download (2015) and went back 40 years; however, there were no data available from the West Pacific in 1976, shortening our data set to 39 years. We did not start earlier than this due to the known issues with the earlier part of the hurricane record. In addition, we only selected TCs that reached tropical storm intensity (18 ms^{-1}), which should also limit the number of missed TCS, as weaker ones would be more likely to go unobserved in the earlier parts of the record.

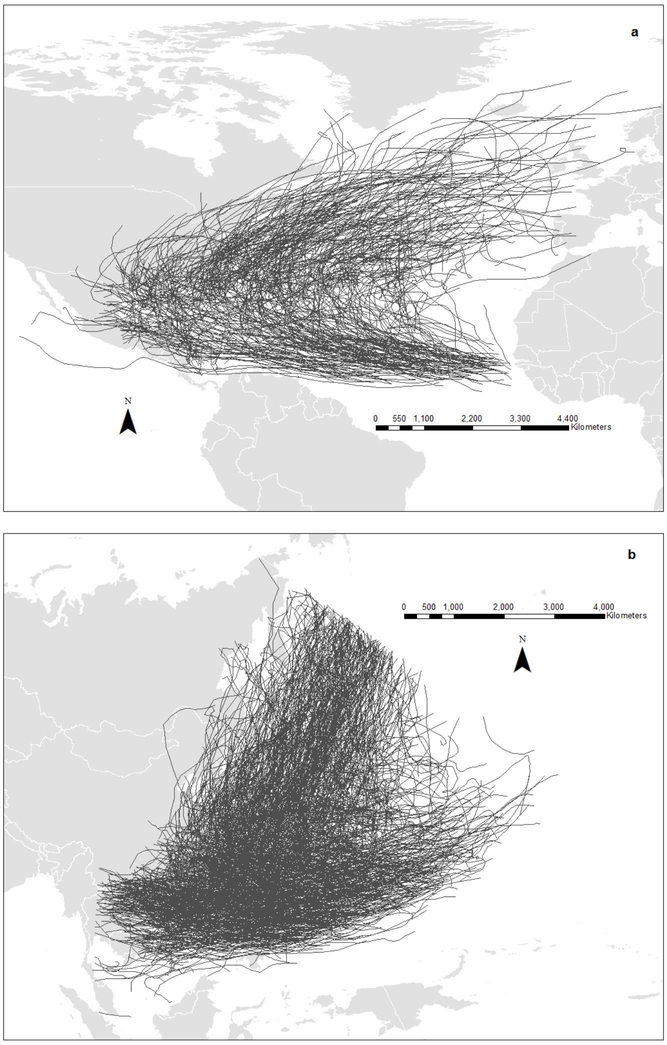

Figure 1. Tropical cyclones (TCs) used in the study in the (**a**) North Atlantic and (**b**) West Pacific basins.

LMI was calculated using the wind measurements from 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 West Pacific basin were projected using the Asia Lambert Conformal Conic projection. The latitude of each LMI was calculated in the attribute table of the shapefile.

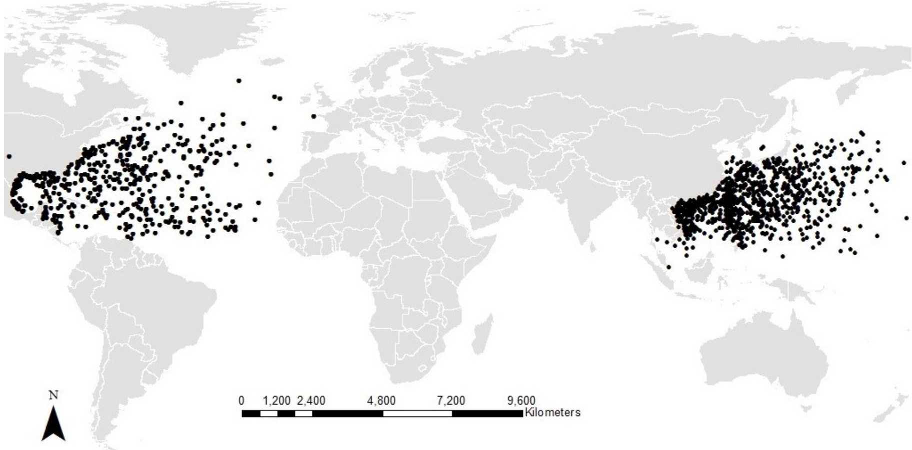

Figure 2. Lifetime maximum intensity (LMI) locations for TCs with wind speeds $\geq$18 ms^{-1} from 1977–2015 in the North Atlantic and West Pacific Oceans.

LMI and landfall location of the most intense (top 25% of maximum wind speeds in each basin) landfalling TCs within the period were plotted 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. The select by location function in ArcGIS was used to extract intense TC tracks that reached their LMI before intersecting land. The distance from each LMI to landfall was measured in an edit session using the measure tool that traced the TC tracks.

2.2. Methods

The data were first explored using descriptive statistics, including the quartiles of LMI latitudes and wind speeds; and bivariate analyses, specifically Pearson product-moment correlations of year, wind speed, and LMI latitude. The latitudinal migration of LMI was assessed for trends in the annual means and moving decadal means using linear regression. Annual means were used because they were the method used to first show the LMI migration [6], and moving decadal means were used because they are helpful to explore overall trends in hurricane data that may be masked by ocean–atmosphere oscillations [18]—for example, the El Niño Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation. This is relevant because [6] show that overall LMI migration is clearer after accounting for the influence of the El Niño Southern Oscillation.

The strongest hurricanes are increasing the most in intensity [5], so we were interested in assessing whether the LMI of TCs of different intensities were migrating at different speeds. We investigated the relationship between intensity and LMI migration trends by finding the linear trends of the moving decadal means for each quartile of LMI intensities.

Finally, we were interested in determining how any change in LMI latitude affects how closely storms reach LMI to land, should they make landfall. We analyzed the most intense landfalling TCs (top 25% in each basin) to determine if there was a trend over time in how far these storms reached their LMI from their eventual landfall location.

3. Results

3.1. Descriptive Statistics

The distribution of wind speeds and LMI locations of the data set are shown in Table 1. Wind speed quartiles are identical for the two basins except for the fourth quartile. These wind speed quartiles are later used to subset the data by intensity. LMI latitude is farther north in the North Atlantic for all quartiles.

Table 1. TC sample size (n) in the North Atlantic and West Pacific Oceans, along with maximum, minimum, and quartile values of wind speed and LMI latitude.

		Wind Speed (ms^{-1})				
	n	**min**	**25%**	**50%**	**75%**	**max**
North Atlantic	473	18	26	33	46	84
West Pacific	954	18	26	33	44	72
		Latitude of LMI (°N)				
North Atlantic	473	10.2	20.1	28.2	33.8	58.9
West Pacific	954	1.5	17.2	21.4	26.6	42.9

Results of the bivariate analyses show that the LMI latitude in the North Atlantic was weakly correlated with both maximum wind speed ($r = -0.12, p < 0.01$) and year ($r = -0.14, p < 0.01$). In the West Pacific, LMI latitude was weakly correlated with maximum wind speed ($r = 0.12, p < 0.01$), but not year ($r = 0.03, p = 0.33$). Interestingly, the correlation between maximum wind speed and LMI latitude were the same strength in both basins, but moving in the opposite direction; stronger storms in the North Atlantic (West Pacific) reached their LMI farther south (north). In the North Atlantic, the latitude of LMI had a slightly stronger relationship with year than maximum wind speed. Neither basin showed a significant relationship ($p < 0.05$) between maximum wind speed and year, indicating no trend in the mean TC intensity.

3.2. Changes in the LMI Latitude

The TCs were aggregated by year to assess changes in annual mean LMI latitude, similar to [6] (Figure 3). A linear regression indicated that the latitude of LMI in the North Atlantic (a) moved 1.2° (95% CI [19.2–−0.5]) south per decade ($p < 0.01$). The bivariate analyses in the West Pacific did not suggest a linear trend in LMI latitude, and this was confirmed using linear regression (0.2° migration per decade, $p = 0.32$).

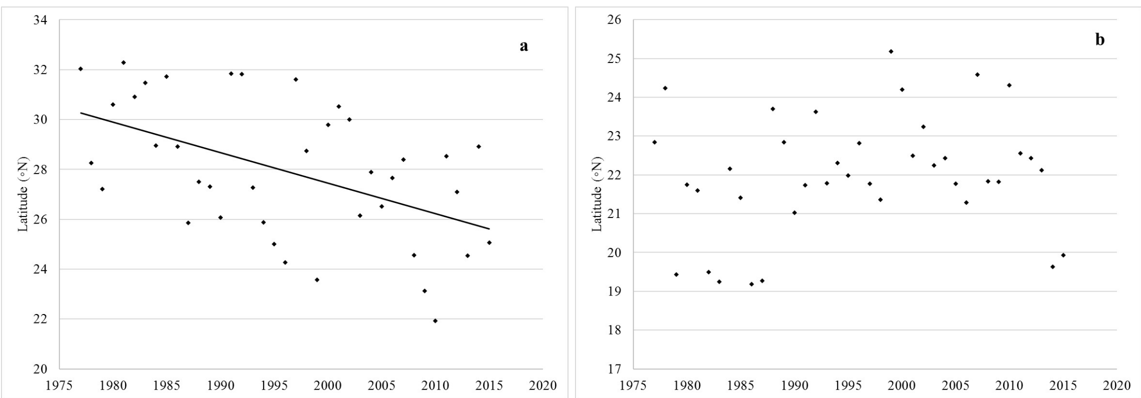

Figure 3. Mean annual LMI latitude in the (**a**) North Atlantic and (**b**) West Pacific basins. The significant linear trend of LMI latitude in the North Atlantic is shown with the solid line.

Next, the data were analyzed using moving decadal means (Figure 4). The first decade was 1977–1986, followed by 1978–1987, and so on. In the North Atlantic there was a linear trend in LMI migration of 1.2° south per decade ($p < 0.01$). In the West Pacific, a poleward trend was evident with a significant linear relationship of 0.6° latitude per decade ($p < 0.01$).

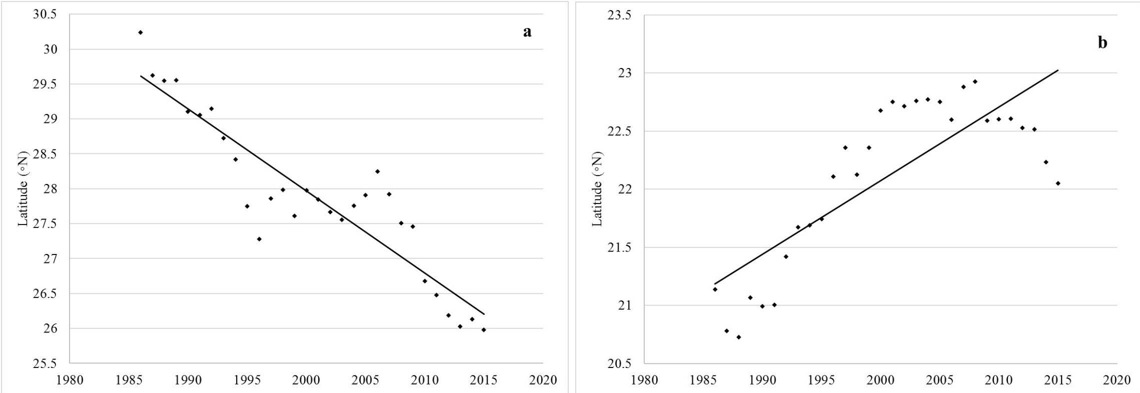

Figure 4. Moving decadal means of LMI latitude in the (**a**) North Atlantic and (**b**) West Pacific basins. The significant linear trends of LMI latitude are shown with a solid line.

3.3. LMI Migration Based on Intensity

The latitude of LMI was subset by intensity to determine if there were different trends in LMI migration depending on maximum wind speed. LMI latitudes were divided into quartiles according to their maximum wind speed (quartile values are given in Table 1). Figure 5 shows the moving decadal means of LMI latitudes for each quartile of TCs in the North Atlantic (a) and West Pacific (b) basins. The strongest TCs are in the fourth quartile. Trends for each quartile are in Table 2. In the North Atlantic, the strongest trend was with the most intense storms, which moved south at a rate of 1.8° per decade. The first and second quantiles also had significant trends, but the slope was not half as steep. The West Pacific also had three significant trends, with all mean LMI latitudes except for those of the third quartile of TCs moving significantly north. The strongest rate of change was in the second quartile (1.4° north per decade), followed by the strongest storms in the fourth quartile (0.9° north per decade).

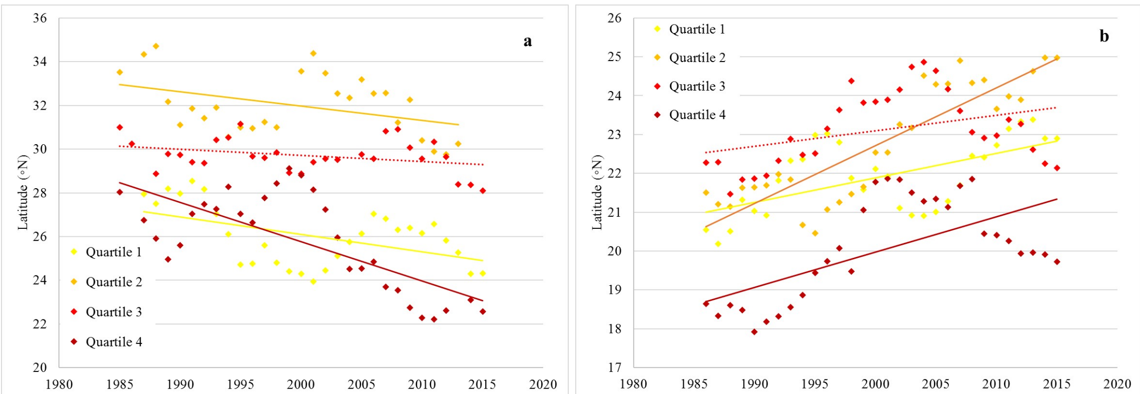

Figure 5. Moving decadal means of the LMI latitude of the strongest quartile of TCs in the (**a**) North Atlantic and (**b**) West Pacific basins. The strongest storms are in the fourth quartile. The significant linear trends ($p < 0.05$) in LMI latitude are shown with a solid line. Dashed lines are shown for the other quantiles.

Table 2. Decadal rate of LMI migration in each basin (° latitude), separated by quartiles of wind speed. The strongest storms are in the fourth quartile. Asterisks (*) indicate a significant trend ($p < 0.05$).

Quartile	1	2	3	4
North Atlantic	−0.8 *	−0.7 *	−0.02	−1.8 *
West Pacific	0.6 *	1.4 *	0.4	0.9 *

3.4. LMI Location Relative to Landfall

The LMI locations of the strongest storms (fourth quartile) were analyzed to see if they are migrating toward or away from land. Linear trends were exhibited in both basins (Figure 6). LMI locations in the North Atlantic moved 91 km/year away from their eventual landfall point ($p < 0.01$). LMI locations in the West Pacific moved 8 km/year closer to their eventual landfall point ($p < 0.01$).

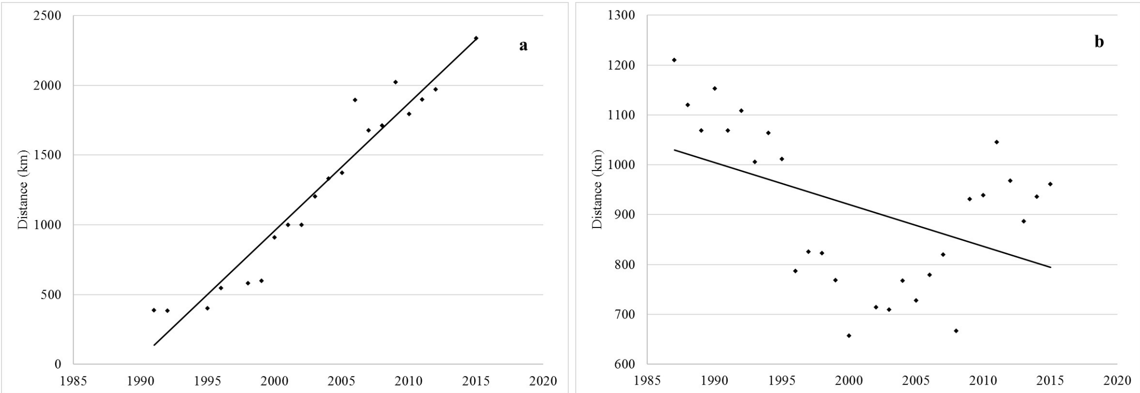

Figure 6. Moving decadal means of the distance from LMI to landfall of the strongest TCs in the (**a**) North Atlantic and (**b**) West Pacific basins. The significant linear trends are shown with a solid line.

4. Discussion

The location of the LMI in the North Atlantic and West Pacific exhibited some trends over the study period. In the North Atlantic, overall trends were for southern LMI migration. A weaker northerly trend was shown in the West Pacific, and was only clear when analyzing decadal means. These results differ from [6], which did not find a significant southern migration in the North Atlantic and found a significant northerly trend in the West Pacific. This is partially due to using a different time frame, with our study beginning 5 years earlier and ending 3 years later; a different TC set, with ours being tropical storms and stronger; and slightly different analysis techniques, with ours including decadal means. Our work demonstrated that the poleward shift of intensities is not apparent in all basins, and in some it is the opposite, especially when removing the weakest TCs.

Analyzing the moving decadal means of LMI latitude supported a concept introduced by [6]: that cyclical patterns are also apparent in LMI migration. While there are linear trends in the decadal means, in the West Pacific a parabolic shape emerges in the overall northerly trend, likely a result of ocean–atmosphere oscillations that provide cyclical changes in the tropical environment (for example, the Pacific Decadal Oscillation). Therefore, it is challenging to discern anthropogenic causes from cyclical patterns of LMI migration in this basin. Additionally, the obvious non-linear trend indicates that adding 5–10 years to the beginning or end of the study period could cause a large change in the linear trend. Shortening our study period to match [6] results in a significant ($p < 0.01$) northerly trend in the annual mean latitude of LMI in the West Pacific basin that was not seen in our time period until we used a decadal mean.

Perhaps the most notable finding here was the extreme southerly movement of the strongest TCs in the North Atlantic basin. The rate that the strongest North Atlantic TCs moved south in our study was nearly twice the rate of the mean poleward global LMI migration (1° latitude per decade) found by [6]. These TCs were part of the inspiration leading to this work, as they have also increased in intensity at a greater rate than their weaker counterparts in the North Atlantic [5]. With this southerly migration, LMI locations of the strongest storms were also migrating away from landfall in the North Atlantic at a rate of nearly 100 km/year, which is encouraging. This was countered by a 8 km/year landward migration of LMI by the strongest storms in the West Pacific, which could have negative consequences for coastal communities. These concepts should be analyzed further, as they begin to demonstrate potential human impacts resulting from any migration of LMI.

The southerly LMI migration in the North Atlantic basin is the reverse of what is expected based on the "expanding tropics" hypothesis. A number of studies have used different metrics to study tropical expansion, and while there are still questions left to be answered, there is a general consensus that the tropics are expanding at a rate up to 1° latitude per decade [19]. Theoretically, this expansion would be accompanied by a poleward shift in TC activity, including LMI latitude, as proposed by [6]. Our work demonstrates that—much like the change in TC intensity over time—the effect of tropical expansion on LMI latitude is not even across basins or TC intensities.

The physical mechanism driving these patterns should be subject to analysis in future work. One possible explanation is the trend in TC genesis location. This was recently explored by [20], which concluded that in the Pacific Ocean there is a poleward migration of conditions favorable for TC genesis, and a southerly trend of genesis locations in the North Atlantic. Thus, the genesis location of TCs in the North Atlantic is moving to the south where there are greater maximum potential intensities. This could impact both LMI location and overall intensity, and could be part of the connection between the increasing maximum intensity of the strongest TCs and the significant southerly migration of their LMI.

This work adds to those emphasizing the importance of understanding the climatology of the most intense hurricanes. These storms have been shown to cause the most damage [21], are increasing in intensity over time [5], have a unique spatial pattern [22], and along some coastlines they cluster over time [18]. Now we suggest that, in some places, the location of their LMI may be migrating faster than weaker TCs, or that their LMI may be getting closer to landfall. Discerning long-term patterns in these intense storms, just like studying LMI migration, can be challenging with the relative brevity of a reliable hurricane database and the low frequency of these events. In the future we aim to use alternate sources of hurricane information to build our knowledge of LMI migration, especially in the most intense TCs.

Acknowledgments: The authors acknowledge the input of Bruce Ralston and Henri Grissino-Mayer during the earlier stages of this work. They appreciate the thoughtful feedback from the reviewers.

Author Contributions: S.A.T. and K.N.E. conceived and designed the experiments; S.A.T. and K.N.E. performed the experiments; S.A.T. and K.N.E. analyzed the data; S.A.T. and K.N.E. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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