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Chapter

The Interannual and Interdecadal Variability in Tropical Cyclone Activity: A Decade of Changes in the Climatological Character

Anthony R. Lupo, Brendan Heaven, Jack Matzen and Jordan Rabinowitz

Abstract

During the last decade, there has been concern that the frequency or intensity of tropical cyclones (TCs) has increased. Also, climate models have shown varying results regarding the future occurrence and intensities of TC. Previous research from this group showed there is significant interannual and interdecadal variability in TC occurrence and intensity for some tropical ocean basins and sub-basins. This work examines global TC occurrence and intensity from 2010 to 2019 and compares this period to the same quantities from 1980 to 2009. The data used here are obtained from publicly available TC archives. Globally, the number of TC occurring over the latest decade is similar to the previous decade. However, while the 40-year trend shows an increase in TC, only intense hurricanes have shown an increase. The Atlantic Ocean and North Indian Ocean Basins show increases in TC activity, especially intense storms. The Southern Hemisphere and West Pacific Region show decreases in TC activity. In the West Pacific, intense TC did not increase, but the fraction of storms classified as intense increased. Only East Pacific TC activity showed no significant short- or long-term trends. Interannual and interdecadal variability in each sub-basin was found and there were some differences with previous work.

Keywords: tropical cyclones, climate change, variability, ENSO, intensity, PDO

1. Introduction

A decade ago, Lupo [1] found no statistically significant long-term trends in global tropical cyclone (TC) activity or in many of the regional basins, although detailed records for some parts of the globe (e.g., the Southern Hemisphere) have only been available since about 1980. This study looked at time series of varying lengths within each ocean basin. This same work showed that there was interannual variability in TC occurrences and intensities found in most ocean basins. However, there was little statistically significant interannual TC variability during the negative or cold phase of the Pacific Decadal Oscillation (PDO), but interannual TC variability with respect to El Nino and Southern Oscillation (ENSO) was enhanced

during the positive or warm phase of the PDO. Lupo [1] also showed some interannual variability in the length of the TC season in different basins as well.

Others (e.g., [2], and references therein) found significant interdecadal TC variability in the Atlantic Region as related to teleconnections such as the North Atlantic Oscillation (NAO) or the Atlantic Multidecadal Oscillation (AMO), and relate these to a relative minimum in this region's TC activity in the late twentieth century and a sharp increase in TC activity for the early twenty-first century. These results were consistent with the results of Lupo [1]. Camargo et al. [3] examine the climatological character of TC including long- and short-range variability in each ocean basin as well. This work is a comprehensive review of those that relate TC activity to intraseasonal phenomena such as the Madden Julian Oscillation (MJO), ENSO, the Quasi-biennial Oscillation (QBO), and others.

Since Lupo [1], others have published results showing that there have been more recent increases in the number of stronger storms in both the Atlantic (e.g., [4, 5]) and the West Pacific basin [6]. The latter showed this trend has been occurring since 1998, but others have demonstrated that the trend has been present in the West Pacific since the 1970s (e.g., [7]). Globally, several studies (e.g., [8, 9]) have demonstrated an increase in the most intense storms and/or the associated precipitation rates [10]. The latest published study [11] examined the global frequency of intense TC from 1979 to 2017 and found statistically significant increases as well. Some have noted that these increases in intense TC are associated with basin-wide changes in the sea surface temperature patterns (e.g., [6]). Others (e.g., [12]) examined the rapid intensification of TC over the Atlantic Region during the latter part of the 20th century as related to climate variability and trends. Additionally, the IPCC [4] fifth assessment report demonstrated no general agreement about the relative contribution of natural and anthropogenic forcing to changes in TC intensity.

The focus on the most intense TC during the last decade is likely due to the fact that many climatological studies have established well the general character of TC climatologies in the world's ocean basins. Additionally, the contributing dynamics to TC formation, development, and decay are well known (e.g. [3, 13, 14], and references therein). At the turn of the twenty-first century, tropical cyclone (TC) activity and how this may change in the future were of great interest to the atmospheric science community (e.g., [15, 16]). Furthermore, there is interest in the observed and potential increase in rainfall rates [10]. Increases in intensity and rainfall rates could threaten vulnerable coastal areas.

The consensus of several global and regional scenarios for TC activity continues to project that the annual frequency will remain similar to today or decrease throughout the twenty-first century, but the intensity will increase (e.g., [4]). This may be due to projected decreases in strong tropical convection, although the confidence in this particular projection is lower. Additionally, these TC projections have been identified as uncertain since high-resolution simulations struggle to adequately capture TC occurrence and intensity [17, 18]. Also, the actual count of TCs is dependent on the different detection methods [19].

However, as discussed above with reference to Lupo [1] and further in that publication, the available time series across each region of the globe is uneven, and the ability to observe TC has continuously improved. There have even been changes in the instrumentation during satellite era and some studies (e.g., [20]) were able to homogenize the most recent satellite-derived data in order to analyze trends in TC occurrence and intensity. Also, changes in the techniques used to determine TC character and intensity have occurred as well (e.g., [21–23]).

The goal of this work is two-fold. The first is to examine the latest decade in TC activity in order to determine if there have been any major changes in global,

regional, or subregional TC frequency since Lupo [1]. The activity of the latest decade will be placed into the context of previous activity going back to 1980 and recent studies where available. By going back to 1980, this work will present the occurrence and intensity of TC in every ocean basin (and sub-basin) where they occur over four decades and this work is one of only a few thus far (e.g., [11]). TC intensity was not available for all ocean basins until approximately 1980 (e.g., [1]). The techniques used here are the same as those found in Lupo [1] and earlier studies in order to facilitate comparisons to these older studies published by this group. The second will examine TC activity with respect to interdecadal variability, and in particular the PDO, in each region in order to determine whether the results of Lupo and Johnston [16] and Lupo [1] remained intact. While the examination of interannual and interdecadal variability of TC is not unique, the study of these quantities over the entire globe and in each TC basin and sub-basin for this recent 40-year period is the first as far as the authors are aware.

2. Data and methods

The data and methods are similar to those used in Lupo [1] and references therein, and more detail regarding some of these subjects can be found there. This study will examine all the globe's ocean basins and includes tropical storm occurrences as well. The global ocean basins (**Figure 1**) are as follows: the North Atlantic, East Pacific, West Pacific, North Indian, Southern Hemisphere (includes South Indian and the South Pacific), and the South Atlantic. Following Lupo and Johnston [16] and Lupo [1], the North Atlantic was divided into west and east along 45°W. The East Pacific is divided along 125°W and 20°N as in Collins [24, 25], while the West Pacific is divided up into 140°E and 20°N following Lupo [1]. The Indian Ocean in the Northern and Southern Hemisphere is divided into west and east along 75°E. The southwest and southeast Pacific are divided by 180° longitude. Both the Indian and SH sub-basin divisions followed Lupo [1]. TCs were assigned to the basin and sub-basin in which they first reached tropical storm status. A study of the background atmospheric and oceanic variables contributing to TC formation is not performed here as it is beyond the scope of this work.
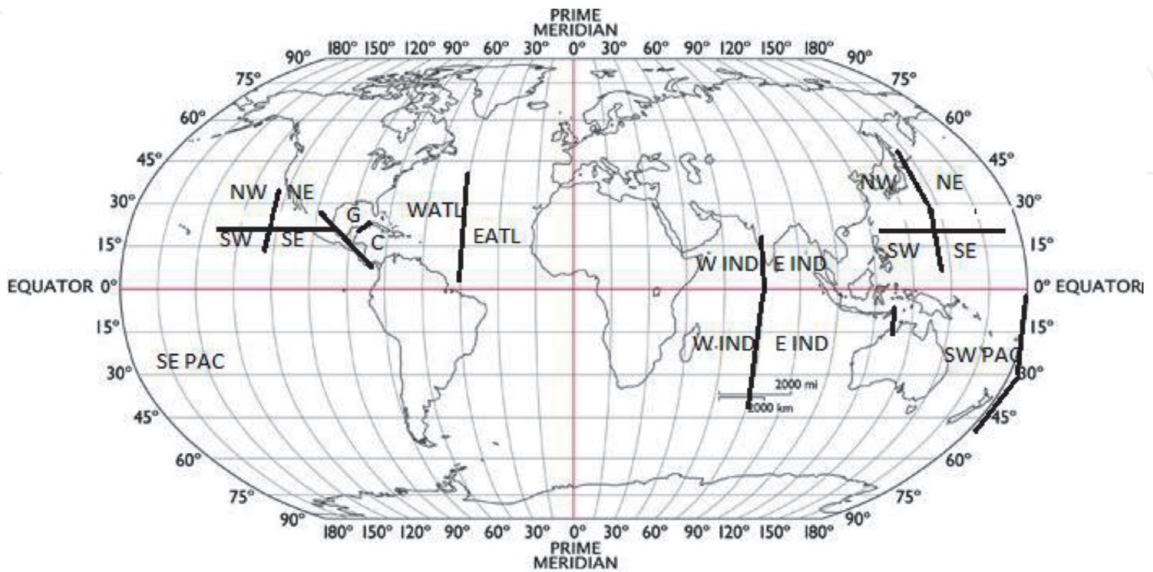
Figure 1.
The globe with the borders of each subregion for the North Atlantic (G = Gulf of Mexico, and C = Caribbean), East Pacific (125°W 20°N), West Pacific (140°E 20°N), northern Indian (75°E), and southern hemisphere (75°E in the Indian and 180° in the Pacific).

2.1 Data

The TC occurrence and intensity data for all basins since 1980 were downloaded via the UNISYS website (http://weather.unisys.com), although these data can also be found in the National Hurricane Center (NHC) or the Joint Typhoon Warning Center (JTWC) archives (e.g., [21]). The TC data since at least 1900 can be found in the International Best Track Archive for Climate Steward-ship (IBTrACS) or the best track data archive [26, 27]. A description of these data sets and their reliability can be found in references, such as Landsea [28], Knapp et al. [26], or Kossin et al. [20]. Here, we use the term TC to include both hurricanes and tropical storms (TSs) following Lupo et al. [29] and references therein. TS refers only to those entities that obtained maximum wind speeds between 35 and 64 kt. The year 1980 was chosen for this study in order that time series of the same length can be compared across the globe since TCs were not categorized in the Southern Hemisphere until that year (see [1]). Also, TC data sets from before the satellite era may be missing TC occurrences that went undetected by ship or aircraft (e.g., [30]). Additionally, this study will compare and contrast briefly the most recent four decades with those previous to 1980 (see [16]) where those data exist (Atlantic Region and West Pacific Region). Hurricane intensity was rendered using the maximum wind speed attained during the lifetime of the storm. However, since wind speed data have relatively large measurement error, the Saffir-Simpson [31] hurricane intensity scale values were used here. In order to further eliminate problems with some of the data as discussed in Lupo and Johnston [16] and later studies, we combined hurricane intensity categories (Category 1 and 2—weak; Category 3, 4, and 5—intense) following Landsea [28].

2.2 Methodology

Arithmetic means and correlations were analyzed, and means were tested for statistical significance using a two-tailed z-score test, assuming the null hypothesis (e.g., [32, 33]). Intensity distributions were also tested using a χ^2 statistical test. These distributions were tested using the total sample climatology as the expected frequency and a subperiod as the observed frequency. The χ^2 test was used to test the intensity distributions (TS and Category 1–5) of the most current decade against those of the previous 30 years as well as to examine the interannual or interdecadal variability of intensities. It has been hypothesized that using the climatological frequency as the "expected" frequency is more appropriate than using an approxi-mated distribution since such analytical distributions (e.g., Poisson distribution) may not adequately represent real-world distributions (e.g., [34]). It should be cautioned that while statistical significance reveals strong relationships between two variables, it does not imply cause and effect. Conversely, relationships that are found to be strong, but not statistically significant may still have underlying causes due to some atmospheric forcing process or mechanism (e.g., [34]). The long-term trends were tested for statistical significance using analysis of variance techniques (ANOVA) and in particular the F-test [32, 33].

The following descriptions can be found also in Lupo and Johnston [16]. The data were stratified by calendar year in the Northern Hemisphere (NH). In the Southern Hemisphere (SH), the tropical cyclone year is defined as the period beginning on July 1 and ending on June 30. For example, July 1, 2018 to July 1, 2019 was defined as 2019 since the majority of the SH TC season takes place from approximately December through April. We then analyzed the annual and monthly distributions of TC occurrence in order to find trends in TC season length or both the total sample and each intensity category.

2.3 Interannual and interdecadal variability

The Japan Meteorological Agency (JMA) El Nino and Southern Oscillation (ENSO) Index was used in this study. A list of El Niño (EN), La Niña (LN), and Neutral (NEU) years used here are shown in **Table 1**. A description of the JMA ENSO Index can be found on the Center for Oceanic and Atmospheric Prediction Studies website (http://coaps.fsu.edu/jma.shtml) hosted by Florida State University. In summary, this index is widely used (see [35]) and is defined by the long-term running mean sea surface temperature (SST) anomalies from the Niño 3 and 3.4 regions in the central and eastern tropical Pacific (e.g., [36]). The SST anomaly thresholds used to define EN years are those greater than +0.5°C, less than − = 0.5°C for LN years, and NEU otherwise. The JMA ENSO criterion defined the EN year as beginning on October 1 and ending on September 30. For example, ENSO year 1982 began on October 1, 1982 and ended on September 30, 1983. This definition, however, was modified here so that the EN year commenced with the initiation of the NH hurricane season (approximately June 1) following Lupo and Johnston [16] and used in Lupo [1]. This modification was necessary since EI Nino conditions typically begin to set in well before October 1, and the period August to October is close to the climatological peak of the hurricane season for the NH. No modification was needed for the SH. Additionally, while the JMA ENSO Index is more sensitive with the definition of LN than other indexes, it is less sensitive overall [37].

The Pacific Decadal Oscillation (PDO) is a 50- to 70-year oscillation described in the late twentieth century (e.g., [38, 39]) within the Pacific Ocean basin. We define the epochs of the PDO as found in Lupo et al. [35] and these are also cataloged at COAPS. The positive phase persisted from 1977 to 1998, while the negative phase has persisted since 1999. The most recent negative phase encompasses the most recent two decades, while the decades of the 1980s and 1990s are largely characterized by the positive phase. Where the data exist before 1980 (the Atlantic and western Pacific Regions), we can use the results of Lupo and Johnston [16] to characterize the negative PDO years from 1947 to 1976.

An in-depth discussion is found in Lupo [1] describing why these two teleconnections were used primarily to define interannual and interdecadal variability, in spite of the fact that many studies (e.g., [2, 3], and references therein) have shown for example that variability in the Atlantic Ocean Basin can be linked to

EN	NEU	LN
1982	1979–1981	1988
1986–1987	1983–1985	1998–1999
1991	1989–1990	2007
1997	1992–1996	2010
2002	2000–2001	2017
2006	2003–2005	
2009	2008	
2014–2015	2011–2013	
2018	2016	
	2019	

Table 1.
The list of ENSO years as found in Lupo et al. [35] and references therein.

teleconnections there. While the NAO-related variations in TC activity can make interpretation of PDO-related hurricane variability more difficult, there is substantial overlap between the PDO and the interdecadal modes of the North Atlantic Oscillation (NAO) [35]. Nonetheless, ENSO is a main driver of interannual TC activity in many ocean basins as demonstrated by many studies (e.g., [3]), and since PDO can be shown to modulate ENSO behavior, the focus here will be on these teleconnections.

3. Global tropical cyclone activity from 2010 to 2019

3.1 A comparison of tropical cyclone activity since 1980

In Lupo [1], tropical cyclone activity was examined within each ocean basin over different time periods. Here tropical cyclone activity since 1980 only was examined for each ocean basin and globally (**Table A1**). Globally, there has been no statistically significant trend in overall TC activity over the last 40 years and this is consistent with recent studies (e.g., [4]) (**Tables A1f** and **2**, **Figure 2a** and **b**). There was also no significant difference in the TC intensity distributions when comparing those of the most recent decade versus the 1980–2009 period. A noteworthy change implied in the global data set was an increase in tropical storm activity since 2000 at the expense of weaker (Category 1 and 2) hurricanes. However, the most recent decade (2010–2019) did not show appreciable changes worldwide when compared with the previous decade (2000–2009) or with the 1980–2009 period. There was, however, a significant upward trend in the number of Category 3–5 and 4–5 storms significant at the 99% confidence level (**Table 2**) consistent with Elsner [6, 10], or Kossin et al. [11].

An examination of each ocean basin demonstrates that only the ATL (**Table A1a** and **Figure 2c** and **d**) and NIND (**Table A1d** and **Figure 2i** and **j**). Regions experienced statistically significant increases for the trend in hurricane activity (at the 95% and 99% confidence levels, respectively) and total TC activity (at the 99% confidence level in both regions) (**Table 2**). Both regions showed slightly more activity in the most recent decade (2010–2019). Testing the distribution of TC intensities in both regions showed no statistically significant difference between the distribution of these for the most recent decade versus 1980–2009 using the χ^2 test. However, the ATL increases are most notable in the tropical storm category (**Table A1a**), but with little change in the weak hurricanes. In the NIND Region, however, these increases were noteworthy only for the number of hurricanes, especially major hurricanes (Category 3 and 4). In both of these regions, the increase in the trend for major hurricanes categories was significant at the 99% confidence level. A comparison to Klotzbach and Gray [2] or Lupo [1] showed that the ATL Region trends found here are consistent with those found for the late twentieth or early twenty-first century identified in those publications. Thus, this region has a longer history of increasing activity. In Lupo [1], the NIND Region showed little trend in TC activity. The upward trends in all categories for the NIND noted here (**Table 2**) could be a real phenomenon or a function of better detection and classification.

The increases were offset by overall decreases in the WPAC (**Table A1c** and **Figure 2g** and **h**) and SHEMI Regions (**Table A1e** and **Figure 2l** and **k**), which would show decreases, but only the decrease in WPAC hurricanes and SHEMI total TC were significant at the 99% confidence level (**Table 2**). Both regions were less active in the most recent decade (2010–2019). In the WPAC (**Table A1c**), the results found here were complex but contradict the results cited in section one.

Figure 2.
The annual occurrence of (a) and (b) global, (c) and (d) Atlantic, (e) and (f) East Pacific, (g) and (h) West Pacific, (i) and (j) North Indian, and (k) and (l) Southern hemisphere tropical cyclones (left) hurricanes (right) from 1980 to 2019. The orange line is the linear trend line in each figure. The abscissa is years and the ordinate is annual occurrence.

|	ATL	EPAC	WPAC	NIND	SHEMI	Globe
TS + Hur	**0.202**[**]	−0.003	−0.044	**0.039**[**]	**−0.102**[**]	0.129
Tot Hur	**0.056**[*]	−0.023	**−0.114**[**]	**0.040**[**]	−0.044	−0.085
Cat 3–5	**0.043**[*]	0.007	−0.007	**0.029**[**]	**0.044**[*]	**0.117**[**]
Cat4–5	**0.032**[*]	0.034	0.030	**0.017**[**]	**0.088**[**]	**0.202**[**]

The value given is the slope of the trend line. Statistically significant values are bold, while those marked with a *, ** are significant at the 95%, 99% confidence level, respectively.

Table 2.
A summary of the statistical significance for trends within each ocean basin.

Examining the major hurricanes, the trend was downward for the Category 3–5 TC, but upward for the Category 4–5 results. Neither trend was statistically significant (**Table 2**), and the significant downward trend was noteworthy in TC Category 1–2 (not shown). While this does not agree with studies like Zhao et al. [6], who have found an increase in intense TC over the WPAC, the decrease in weaker TC means that a greater percentage of WPAC TC was in the major category. During the past two decades, about 60% of TC were classified as major compared to 50% in the two decades prior to those (see also [1]). In spite of a greater ratio of more intense TC in the WPAC, the intensity distributions were not significantly different in either region when testing the intensity distributions.

In the SHEMI, the number of total TCs has decreased significantly, but the number of Category 3–5 and Category 4–5 TCs increased and these trends were significant at the 95% and 99% confidence level respectively (**Table 2**). The overall decrease was driven by decreases in the number of TS and a decrease in Category 1–2 storms (**Table A1e**) significant at the 99% confidence level (not shown). The 2010–2019 decade showed decreases overall and in the number of hurricanes from the previous decade (2000–2009), and this decade was less active than the last decades of the twentieth century (**Table A1e**). The most recent decrease continued the overall decrease found in Lupo [1]. As for the WPAC however, the percentage of major hurricanes was higher (55%) for the early twenty-first century compared to the late twentieth century (43%).

The EPAC Region showed very little trend throughout the period (**Table A1b, Figure 2e** and **f**) in any category, including no statistically significant trend in the major hurricane categories (**Table 2**). This result is similar to that of Lupo [1]. However, it was clear that the 2010–2019 period in the EPAC was more active than the previous two decades suggesting interdecadal variability. This will be studied below. Additionally, testing the distribution of TC intensities for this region shows
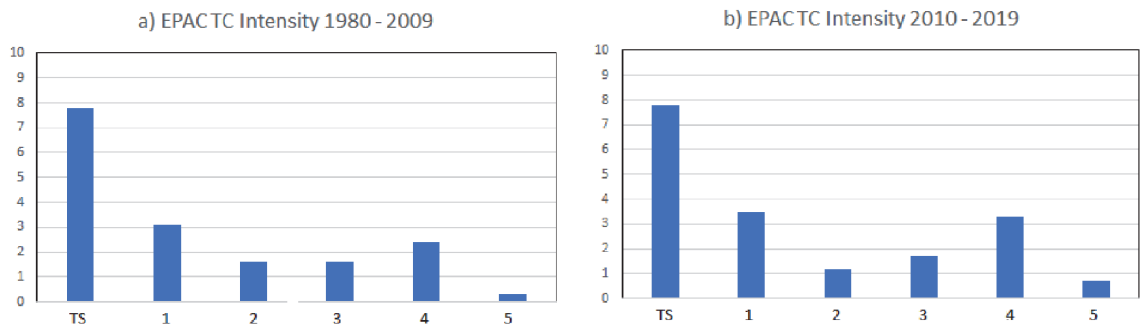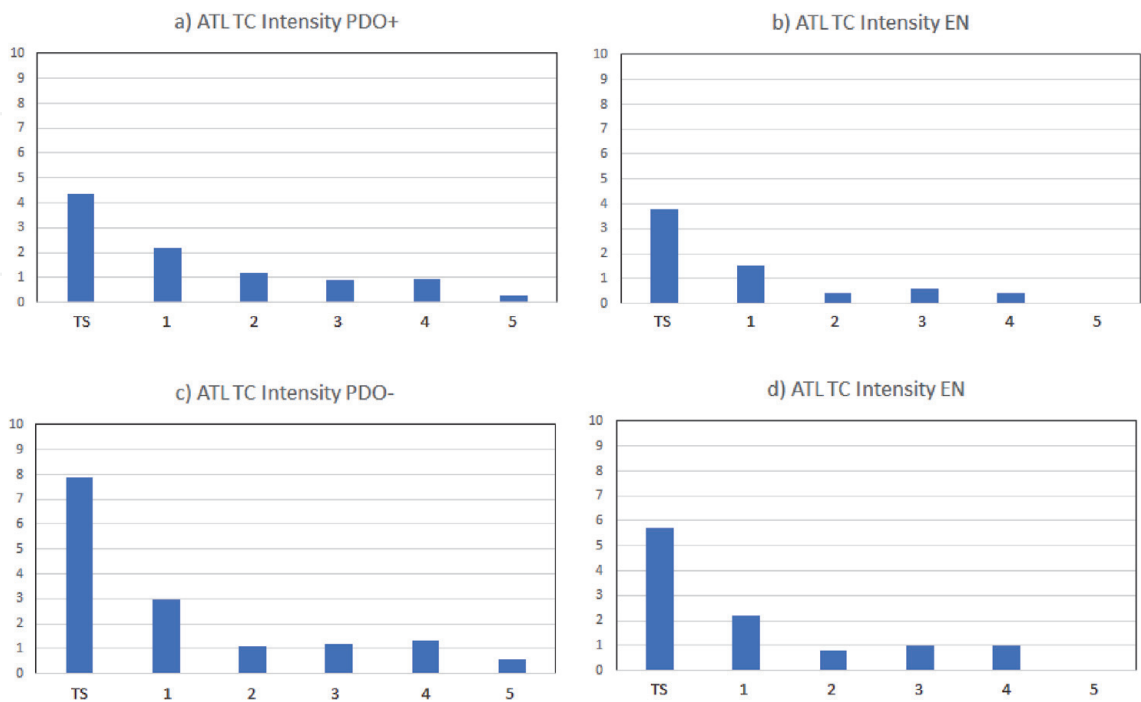
Figure 3.
The TC intensity distributions in the EPAC region for (a) 1980–2009 and (b) 2010–2019. The abscissa is TC intensity and the ordinate is annual occurrence.

that the distribution of TC from 2010 to 2019 was similar to that for the period 1980–2009 at the 95% confidence level when using the χ^2 test (**Figure 3**). This is the only region in which the distributions were similar to an acceptable degree of confidence.

3.2 Interannual and interdecadal variability

In this section, the 2010–2019 results are partitioned by ENSO phase in order to compare these results to those of Lupo [1] and Lupo and Johnston [16]. As shown in Lupo et al. [35], this most recent decade was still classified as a negative PDO. Thus, to examine interannual variability, a comparison was made to the previous decade and interdecadal variability was examined by comparing to the decades of the 1980s and 1990s (**Table A2**). These decades were primarily positive PDO years (1977–1998). This study also provides an opportunity in some ocean basins to compare to the previous negative PDO epoch in order to determine whether the current negative PDO epoch is comparable or if there are differences that may be due to enhanced satellite coverage or if these differences could be physical. The results here were also compared by sub-basin within each global region.

An examination of the Atlantic Region activity (**Table A2a**) demonstrates that there were more TCs observed during LN and NEU years during the latest decade, and this activity was consistent with that of the previous decade. A comparison to the activity during the 1980s and 1990s demonstrated that while there were more TCs overall (significant at the 95% confidence interval when testing the means), the ENSO variability was similar. During each decade, EL years were 30% (or greater) less active than during other years. Thus, there was no significant difference between ENSO variability across the positive phase of the PDO and the current negative phase in spite of a more active negative PDO phase when testing the means in **Table A2a**. Previous studies (e.g., [1]) showed similar results, with the exception that the negative PDO phase showed weaker ENSO-related variability. Additionally, the ENSO variability with respect to TC intensity distributions was similar in that the comparison of the EN years to all years in each phase of the PDO (**Figure 4**)

Figure 4.
The TC intensity distributions for (a) all PDO+ TC, (b) all PDO+ EN TC, (c) all PDO − TC, and (d) all PDO − EN TC in the ATL region.

and these were similar at the 90% confidence level. The LN year distributions were different from either the EN years or those overall, but not at standard levels of significance.

A comparison of **Table A2a** to the results of Lupo and Johnston [16] demonstrated that both the current (since 1999) and the previous (1947–1976) negative PDO epoch were more active than the positive PDO epoch (1977–1998). This result is similar to that of Klotzbach and Gray [2], who also show the mid-twentieth century and early twenty-first century were more active times for TC occurrence in the Atlantic Region compared to the latter twentieth century. This also supports the contention of overlap between multi-decadal epochs of the PDO and Atlantic Region teleconnections described in Section 2.3. However, in Lupo and Johnston [16], the number of TCs reaching hurricane strength did not vary at all with respect to ENSO from 1947 to 1976. Their study did not include tropical storms. Thus, it would be difficult to state with certainty that the difference between the results above and the Lupo [1] study are real as they may be a result of not counting TS in the earlier study or the lack of satellite observations. The non-count of TS is supported since if TSs are not included in the current negative PDO period, the ENSO variability in this phase is much weaker.

An examination of the regional occurrence of TC within the Atlantic over the latest decade (**Table A2a**) demonstrates that the western Atlantic is the most active sub-basin and that the ENSO variability within this region is minor. The Gulf and Caribbean sub-basin TC activity was also unchanged as EL years are much less active in these two areas. These results agree with the previous studies from this group and others (see [3]). The only substantial difference between the results presented here and the previous results was that the eastern Atlantic was significantly more active (at the 99% confidence level) even when considering the small sample size. This may be due to increased SSTs over this part of the Atlantic during the last decade (e.g., [40]). A comparison of the length of the TC season (not shown here) to previous results [1] would demonstrate that the Atlantic Region TC season may be beginning about 2 weeks earlier than June 1 as TCs were observed in May for 5 of the 10 years during this decade.

In the East Pacific Region (**Table A2b**), the most recent decade shows ENSO variability that is opposite of the Atlantic Region, in that there are more TCs during EL years than during LN years due to the warmer sea surface temperatures there. This is similar to Collins [24] or Lupo [1]. There was also little difference in TC numbers across the positive and current negative PDO epoch, and their intensity distributions were similar, a result significant at the 95% confidence level (as in **Figure 3**). When taken together, the first two decades of the 40-year period show ENSO variability similar to the latter two decades in that there were about 30–35% fewer TC in LN years. When testing the means, this result was statistically significant at the 95% confidence level. Testing the TC intensity distributions demonstrates that LN years were similar to the overall distributions at the 95% confidence level during both phases of the PDO in a manner similar to **Figure 3**. Even the EN year TC intensity distributions are similar to the overall intensity distribution in the positive PDO phase at the 90% confidence level. Only the EN years TC intensity distribution during the negative phase of the PDO was different from the overall distribution, but not at statistically significant levels.

In **Table A2b**, it is apparent that the East Pacific Region is dominated strongly by activity in the southeast quadrant and this has not changed across any decade or PDO epoch. TC occasionally form further up the Central American and North American coast in the northeast quadrant, but only during LN and NEU years, while TC formed rarely in the northwest quadrant. The southwest quadrant TC activity did account for about 16% of the East Pacific Region activity and the ENSO

variability in this quadrant was similar to the previous decades and also similar to that of the southeast quadrant (e.g., Camargo et al. [3] and references therein). The only difference is that the most current decade showed stronger ENSO variability, but this was not statistically significant. Finally, there was no appreciable change in the length of the East Pacific TC season.

As shown above, there has been a decrease in West Pacific hurricanes. **Table A2c** confirms that the TC activity of the most recent decades is less than that of the previous three decades, which can be assumed to be real since satellite coverage has been comprehensive since 1980. However, it is difficult to attribute this decrease to interdecadal variability when comparing to Lupo [1] since the TC activity from the 1940s through the 1970s occurred during an era with less satellite coverage. This same study concluded that there was no significant West Pacific Region interdecadal or interannual variability. Overall, LN years were 20% less active than EN years from 1980 to 2019. For this period and region, this is significant at the 95% confidence level. Thus, there is a strong correlation between the interannual variability within this region and the East Pacific Region (e.g., [3]). An examination of the TC intensity distributions (**Figure 5**) shows that the distribution of negative and positive PDO is similar at the 90% confidence level using the χ^2 test. This is also true for the EN year TC distributions in relation to the intensity distributions for the positive or negative phase of the PDO (**Figure 5**).

Table A2c also demonstrates that the occurrence of TC by quadrant in the West Pacific over the most recent decade was similar to that found in the earlier decades and Lupo [1]. In short, the southwest quadrant is the most active and shows only marginal (insignificant) interannual and interdecadal variability. The southeast quadrant is associated with 30% less TC activity than the southwest, but very strong (statistically significant at the 95% confidence level) ENSO variability. There were two to four times more TCs in the southeast quadrant during EN years, a result that agrees with many studies (e.g., [1, 3]). The recent decreases noted above for the West Pacific Region overall was distributed among the four sub-basins, though as a percentage, the decrease was largest (approximately 35% less) for the northeast quadrant. Additionally, the active southeast quadrant in the West Pacific during EN
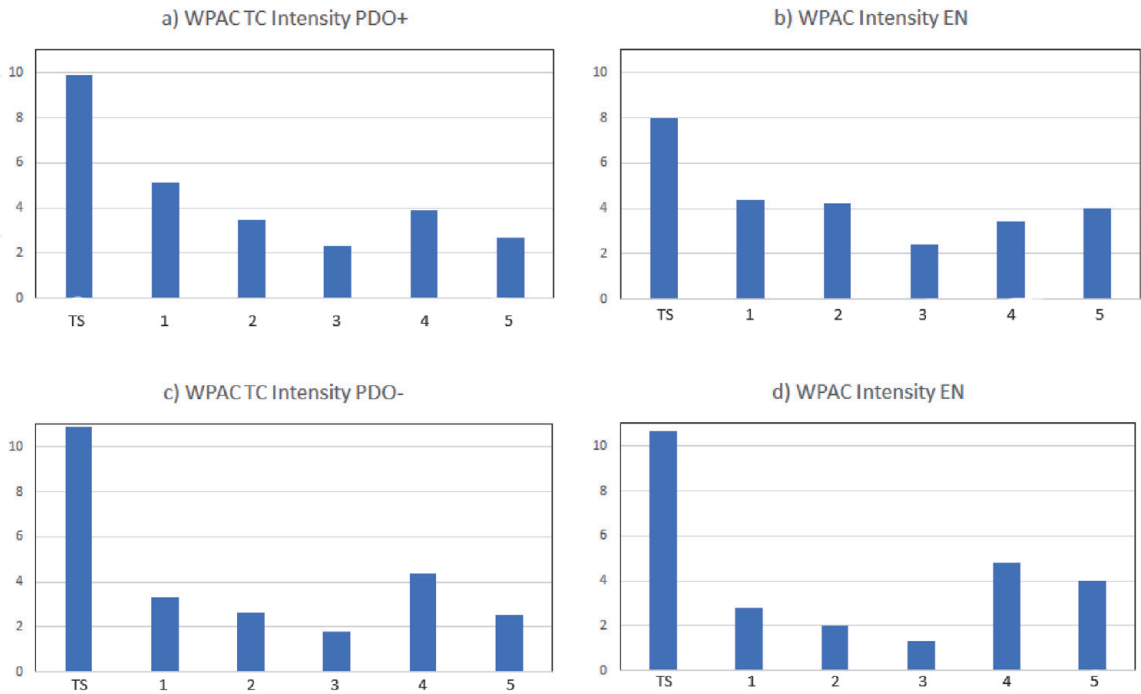
Figure 5.
As in Figure 4, except for the West Pacific region.

years combined with the active southwest quadrant for the East Pacific supports the conclusions of Camargo et al. [3], Lupo [1] and others in that during El Nino years, the Pacific is active across the basin for EN years, while during LN years activity was centered closer to their respective quadrants for both regions. Like the East Pacific, there was no significant change noted in the length of the TC season here (not shown).

In the North Indian Ocean Basin, there was an increase in the number of TC occurrences as shown above, and **Table A2d** suggests that this was driven primarily by increases in the western Indian Ocean Region including the Arabian Sea. This includes the number of major storms. Since the regional classification for the intensity of these storms began in 1977, there is no need to compare this region or the Southern Hemisphere results (this region began reporting intensity in 1980) to earlier results. **Table A2d** also demonstrated that EN years were slightly more active than other years, and this is opposite that of the previous three decades. Thus, there are no conclusions that can be drawn about ENSO variability, nor about the interdecadal variability. However, Ng and Chan [27] showed that there was strong variability on the 5-year timescale in this region linked to the Indian Ocean Dipole (IOD).

An examination of TC intensity distributions (not shown) shows that regardless of how the results are stratified in the North Indian Ocean Region, the distributions are similar to the overall distribution at the 95% confidence level or higher. The only exception was the distribution of TC intensities in LN years during the positive phase of the PDO were different, but not at standard levels of significance. The reason for the lack of variability in TC intensities in this region may be the less frequent occurrence of storms in this region. Finally, there was no change in the TC season here (not shown) and this was identical to the results of Lupo [1] and references therein who showed that this region possessed a double peak in activity (May–June and October–December), which is associated with the annual migration of the Intertropical Convergence Zone.

The decrease in Southern Hemisphere variability shown in **Table A2e** for the most recent decade (2010–2019) continues the trend identified when comparing 2000–2009 or the previous two decades. Like the NIND Region, there are too few years to attribute these decreases to interdecadal variability as of yet. When examining the sub-basins, the decreases over the past two decades were primarily the result of fewer TC in the East Indian Ocean and to a lesser extent over the southwest Pacific. Additionally, during this decade, the TC season extends from October to April, which is similar to the previous decades [1]. Lastly, an examination of the distribution of TC intensities for the positive versus negative PDO demonstrated the distributions were different, but not at standard levels of significance.

The overall interannual variability during the most recent decade showed more TC during EL years, which was counter to the results of the previous three decades (**Table A2e**). This variability, however, was not significant at acceptable levels of confidence. Lupo et al. (2011) found weak ENSO-related variability, which was marginally significant with more TC occurring during LN years. Examining the sub-basins exposed an error in assigning the ENSO year in Lupo [1] (see their Table 17) for these values only. The overall results were consistent between this study and the Lupo's [1] study. The distribution of TC intensities during EN and LN years compared to the negative PDO years showed these distributions were similar at the 99% and 95% confidence level, respectively. During PDO positive years, the same comparison showed similarity at the 95% and 90% confidence level, respectively (not shown).

A discussion of the SHEMI sub-basin results (**Table A2e**) demonstrates that TC numbers in the West Indian Ocean Basin demonstrate the most current decade was

slightly more active than the previous 30 years. EL years were more active over all decades than LN years observing nearly double the TC activity. This is then opposite to what was reported by Lupo [1] as that study reported more TC in LN years. The East Indian Ocean Basin saw the largest decreases as in the previous 30 years, as 11.3 TC events per year were reported. Here, the results show that for the latest decade only 7.7 TCs per year were observed, representing a decrease of about 33%. This was nearly equal to the total decrease in SEMI TC overall. More importantly, in the previous 30 years, LN season TC outnumbered EN season TC by more than two to one. For the latest decade, LN years experienced only 20% more TCs per season. This preference for LN years as in the West Indian Ocean Basin was of the opposite sense reported in Lupo [1]. However, the results presented here now agree with results for the East Indian and West Pacific numbers reported for these regions in earlier studies (e.g., [3], and references therein).

Only in the southwest Pacific were the observed TCs and their interannual variability in the current decade consistent with those of the previous 30 years, showing a slight preference for LN years. Thus, the coding error of Lupo [1] did not have a major impact on the results reported for this sub-basin only. The southeast Pacific was the least active TC region of the SHEMI outside of the South Atlantic, and the occurrences of TC in the latest decade were consistent with the previous three. The latest decade showed only a slight preference for TC occurrences in EL years, and this was consistent with the three previous decades except that the previous decades saw stronger disparities between annual TC occurrences in EL years versus LA years. The ENSO variability in this sub-basin was opposite to what was reported in Lupo [1].

Globally, there were 79.5, 90, and 92 TCs that occurred during LN, NEU, and EN years, respectively, during the last decade. This compares to 82, 91.3, and 85.7 TCs occurring during these years over the previous decade, respectively. The comparative numbers for the 1980–1999 period revealed there were 83.3, 88.8, and 85.6 TCs that occurred per LN, NEU, and EL year, respectively. Thus, the most recent decade demonstrates slightly different ENSO variability from that of the previous three decades, but this difference is not statistically significant. Over the entire 40-year period, these TC occurrence numbers were 81.8, 89.7, and 87.4, during LN, NEU, and EN years respectively.

4. Summary, discussion, and conclusions

In this chapter, the global tropical cyclone activity for 2010–2019 was examined and compared firstly to the TC activity of the previous decade (2000–2009) and then to those occurring from 1980 to 1999. By doing so, we compared the results here to the previous results reported in works such as Camargo et al. [3] or Lupo [1]. The data sources used here were the same as those used in that study. The definitions for the TC season, basins, sub-basins, and internannual and internannual variability were identical to those used in Lupo and Johnston [16] and Lupo [1]. The statistical tests used here can be found in standard statistics text books.

Global TC activity in general during the latest decade was very similar to that of the previous decade and within most sub-basins there were broad similarities as well. However, this study found some key differences from Lupo [1]. The following results are new here.

These are:

- Globally, there were no statistically significant increases or decreases in overall global TC activity although the trend in the number of storms has shown

increases. The number of intense storms (Category 3–5) showed a statistically significant increase over the 40-year period similar to IPCC [4], Kossin et al. [11], and others. The number of TSs also increased, but this was not statistically significant. These increases in these TCs were found in most global basins. Only the number of Category 1 and 2 storms decreased, especially since 2000.

• In the ATL Region, the number of TCs during 2010–2019 was similar to 2000–2009. The overall 40-year trend was upward in the total number of TCs, hurricanes only, and intense hurricanes. These were all statistically significant. The interannual variability over the latest four decades was similar in that there were more TCs during LN years (about 30% more). Additionally, the ATL TC season during the 2010–2019 period started about 2 weeks earlier than the previous decades, while the eastern Atlantic observed an increase in TC activity.

• While the intensity distributions were different when comparing negative and positive phases of the PDO, this result was not statistically significant. Also, the distributions of LN and EN TC intensities were compared to the total sample within each phase of the PDO, and the EN intensity distributions were similar at the 90% confidence level.

• In the EPAC, few differences in the climatological character of TC were noted when compared to Collins [24, 25] or Lupo [1]. When comparing the TC intensity, distributions for each phase of the PDO or with respect to ENSO showed that these distributions were similar at standard levels of significance except when comparing the distribution of EN year TC intensities to the distribution of positive PDO TC.

• Other studies showed significant increases in the number of intense TCs within the WPAC. Such an increase was not found here, but significant decreases in the number of Category 1 and 2 storms resulted in an increase in the proportion of WPAC TCs classified as intense. The decrease in the number of TC basin-wide was distributed approximately evenly across each quadrant. In this region, the TC intensity distributions were similar for each phase of the PDO at the 90% confidence level. This same result was found when comparing EN year TC intensities to the total distribution in each PDO phase.

• Within the IND Region, there were significant increases in TC for the latest decade and over the entire 40-year period for total TC occurrence, Category 1 and 2 storms, and intense TCs and all these trends were statistically significant. These increases were especially evident within the western Indian Ocean Basin and Arabian Sea. All TC intensity distributions tested for interannual and interdecadal variability were similar to each other at standard levels of significance.

• In the SHEMI, the 40-year trends showed significant decreases in TC frequency overall including the number of TSs and Category 1 and 2 hurricanes. But there was a significant increase in the number of intense storms. The number of TCs observed over the latest decade was the lowest in the 40-year period and proportion of TCs reaching Category 3 or higher increased. In this region, the positive and negative PDO TC intensity distributions were different, but not at standard levels of significance. The EN and LN year TC intensity distributions in each phase of the PDO were similar to the total sample for that PDO phase.

- There was no significant SHEMI interannual variability overall, but the latest decade showed more TCs in EN years as compared to LN years. This was different from the previous 30 years. A coding error found in the Lupo [1] results showed that the variability associated with ENSO was opposite that reported in Lupo [1] for three of the four sub-basins.

Acknowledgements

Appendix

See Appendix **Tables A1** and **A2**.

Category	1980–1989	1990–1999	2000–2009	2010–2019	1980–2019
a. Atlantic					
TS	4.1	4.6	7.7	8.1	6.1
Cat. 1,2	3.5	3.9	3.7	4.4	3.9
Cat. 3–5	1.7	2.5	3.5	2.7	2.7
Cat. 4,5	1.0	1.4	2.1	1.7	1.6
Tot Hur	5.2	6.4	7.2	7.1	6.5
TS + Hur	9.3	11.0	14.9	15.2	12.6
b. East Pacific					
TS	8.6	5.6	9.1	7.8	7.8
Cat. 1,2	5.4	4.5	4.4	4.7	4.7
Cat. 3–5	4.6	5.5	2.8	5.7	4.7
Cat. 4,5	2.3	3.9	1.8	4.0	3.0
Tot Hur	10.0	10.0	7.2	10.4	9.4
TS + Hur	18.6	15.6	16.3	18.2	17.2
c. West Pacific					
TS	9.7	10.3	10.4	11.3	10.4
Cat. 1,2	8.1	9.1	6.5	5.1	7.2
Cat. 3–5	8.4	9.0	9.5	8.3	8.8
Cat. 4,5	5.4	7.3	8.0	6.3	6.8
Tot Hur	16.5	18.1	16.0	13.4	16.0
TS + Hur	26.2	28.4	26.4	24.7	26.4
d. North Indian Ocean					
TS	3.7	2.9	4.0	3.2	3.4
Cat. 1,2	0.5	1.3	0.6	1.1	0.9
Cat. 3–5	0.2	1.0	0.5	1.2	0.7
Cat. 4,5	0.1	0.7	0.4	0.8	0.5

Category	1980–1989	1990–1999	2000–2009	2010–2019	1980–2019
Tot Hur	0.7	2.3	1.1	2.3	1.6
TS + Hur	4.4	5.2	5.1	5.5	5.0
e. Southern Hemisphere					
TS	14.6	12.8	13.0	12.0	13.1
Cat. 1,2	8.0	7.8	5.6	5.3	6.7
Cat. 3–5	5.0	7.3	7.1	6.3	6.4
Cat. 4,5	1.6	4.8	4.5	4.8	3.9
Tot Hur	13.0	15.1	12.8	11.6	13.1
TS + Hur	27.6	27.9	25.8	23.6	26.2
f. Global					
TS	40.7	37.3	44.4	43.7	41.3
Cat. 1,2	25.5	26.6	21.0	20.9	23.4
Cat. 3–5	19.8	25.3	23.2	24.2	23.2
Cat. 4,5	10.4	18.1	16.7	17.6	15.6
Tot Hur	45.4	51.9	44.3	44.8	46.6
TS + Hur	86.1	88.2	88.7	88.5	87.9

Table A1.
The decadal mean number of tropical storm (TS), category 1–2, category 3–5, category 4–5, total hurricanes, and total TC for each decade from the 1980s to the 2010s and for the entire period within each global ocean basin and over the entire globe.

a. Atlantic	All	CRBN	GULF	WATL	EATL
1980–1999/2000–2009					
LN (3/1)	12.7/15.0	2.3/2.0	3.0/4.0	3.7/7.0	3.7/2.0
NEU (12/6)	10.1/17.3	1.0/3.3	1.9/3.5	5.8/7.0	2.2/3.7
EN (5/3)	7.0/10.0	0.4/1.3	1.4/1.7	4.0/6.3	1.2/1.3
Total	10.2/14.9	1.1/2.6	1.9/3.0	5.1/6.8	2.2/2.8
2010–2019					
LN (2)	18.0	4.0	2.0	6.5	5.5
NEU (5)	16.2	1.6	3.8	6.5	4.4
EN (3)	11.3	1.3	0.7	5.3	4.0
Total	15.2	2.0	2.5	6.2	4.5
b. East Pacific	All	NW	NE	SW	SE
1980–1999/2000–2009					
LN (3/1)	12.3/14.0	0.0/0.0	1.7/1.0	1.7/3.0	9.0/10.0
NEU (12/6)	17.9/15.7	0.1/0.2	1.1/0.8	2.8/2.2	13.8/12.5
EN (5/3)	18.4/18.3	0.0/0.0	0.4/0.3	3.2/4.0	14.6/14.2
Total	17.1/16.3	0.1/0.1	1.0/0.7	2.7/2.8	13.3/12.7
2010–2019					
LN (2)	13.0	0.5	0.5	0.5	11.5

	All	NW	NE	SW	SE
NEU (5)	17.2	0.0	0.4	2.0	14.8
EN (3)	23.3	0.0	0.0	5.7	17.7
Total	18.2	0.1	0.3	2.8	15.0
c. West Pacific	**All**	**NW**	**NE**	**SW**	**SE**
1980–1999/2000–2009					
LN (3/1)	22.7/25.0	3.7/4.0	3.3/6.0	13.0/11.0	2.7/4.0
NEU (12/6)	28.4/26.7	2.6/3.0	3.7/3.3	13.0/13.2	9.2/7.2
EN (5/3)	27.4/26.3	2.2/3.3	1.6/3.0	10.8/9.3	12.8/10.7
Total	27.3/26.4	2.7/3.2	3.1/3.6	12.5/11.8	9.1/7.9
2010–2019					
LN (2)	20.1	4.0	1.0	11.0	4.0
NEU (5)	26.2	2.6	3.4	12.6	7.6
EN (3)	25.0	2.7	1.0	10.3	11.0
Total	24.7	2.9	2.2	11.6	8.0
d. North Indian	**All**	**West**	**East**		
1980–1999/2000–2009					
LN (3/1)	6.0/6.0	2.3/2.0	3.7/4.0		
NEU (12/6)	4.5/5.0	1.2/1.5	3.3/3.5		
EN (5/3)	4.8/5.0	0.8/1.3	4.0/3.7		
Total	4.8/5.1	1.3/1.5	3.6/3.6		
2010–2019					
LN (2)	4.5	1.5	3.0		
NEU (5)	5.8	2.6	3.2		
EN (3)	5.7	3.0	2.7		
Total	5.5	2.5	3.0		
e. Southern Hemisphere	**All**	**W IND**	**E IND**	**SW PAC**	**SE PAC**
1980–1999/2000–2009					
LN (2/2)	30.5/28.0	4.0/5.5	15.0/14.5	8.0/5.5	3.5/2.5
NEU (13/6)	27.8/25.0	6.1/5.7	12.5/11.8	7.2/4.7	1.9/2.8
EN (5/2)	26.6/26.0	6.6/9.5	6.8/6.5	6.6/6.5	6.6/3.5
Total	27.8/25.8	6.0/6.4	11.4/11.3	7.1/5.2	3.3/2.9
2010–2019					
LN (2)	22.5	4.0	8.5	7.5	2.5
NEU (4)	22.8	6.5	8.3	4.8	3.3
EN (4)	25.2	8.5	6.8	6.8	3.0
Total	23.6	6.8	7.7	6.1	3.0

Table A2.
The mean annual TC occurrence stratified by ENSO phase and sub-basin for the (a) ATL, (b) EPAC, (c) WPAC, (d) NIND, and (e) SHEMI.

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