The Interannual Variability of Hurricane Activity in the Atlantic and East Pacific Regions.

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Abstract

The investigation of the interannual and interdecadal variations in hurricane activity has been an important topic of study lately, especially with regard to their implications for climate change issues. On the interannual time-scale, the El Niño and Southern Oscillation (ENSO) phase has been correlated with hurricane activity in the Atlantic and Eastern Pacific Ocean Basins. For example, various atmospheric and oceanic parameters that influence hurricane development become significantly altered during an El Niño event, leading to suppressed easterly wave development and growth in the Atlantic, but more activity in the Eastern Pacific Ocean basin. This study examined the interannual variability of hurricane intensity (measured as wind speed and interpreted through the Saffir-Simpson Scale) from 1938 through 2007 in the Atlantic and 1970 through 2007 in the Pacific basins, respectively. These data were then compared with the occurrence of El Niño/La Niña events as defined using the Japan Meteorological Association (JMA) index. El Niño/La Niña variability superimposed on variability associated with the Pacific Decadal Oscillation (PDO) was also examined here. Not surprisingly, during an El Niño year the intensity of Atlantic hurricanes was found to be weaker than during a neutral year or a La Niña year, but these conclusions were opposite in the Eastern Pacific Ocean basin. There were also significant differences found in hurricane intensity between El Niño and La Niña years when the PDO was in phase 1 (warm phase), rather than when the PDO was in phase 2 (cool phase). This study also examined the interannual variation in hurricane intensity by genesis region (i.e. Atlantic: the eastern and western Atlantic Ocean Basins, the Caribbean, and the Gulf of Mexico; Eastern Pacific: divided into quadrants using 20^{o} N and 125^{o} W). Finally, the utility of this information in a long-range forecast application is demonstrated.

1. Introduction

While the interannual variability of hurricane activity has been studied extensively over the last few decades, there has been a recent increase in the interest of the *interdecadal* variability of hurricane activity (e.g., Henderson-Sellers et al. 1998; Emanuel, 2005; Webster et al. 2005; Schultz, 2007). This interest has been prompted by several active hurricane years in the Atlantic Ocean basin, as well as concern about changes in hurricane frequency that may be a result of changes in Earth's climate. These active years included the 2004 season during which several storms struck Florida, and the 2005 season which was the most active hurricane season since 1933. Some studies, e.g., Lupo and Johnston (2000) (*hereafter LJ00*), suggested that there is significant interdecadal variability in the occurrence and intensity of Atlantic region hurricane activity, and that this variability may be linked to the Pacific Decadal Oscillation (PDO).

More specifically, LJ00 found that there was a change in the behavior of interannual variability of tropical cyclone occurrences in the North Atlantic as related to the El Niño and Southern Oscillation (ENSO). During the negative phase of the PDO (1947-1976), they found little ENSO related variability in the number and intensity of hurricanes basin wide. However, during the positive phase of the PDO (1977 – 1999) they found that there was strong interannual variability between El Niño and La Niña years. During La Niña years, there were more and stronger hurricanes overall even though there were fewer months with significant hurricane activity. Also, there were more Caribbean and Gulf region hurricanes during La Niña years. Additionally, studies have shown that since 1999 (see Lupo et al. 2007 and references therein), the Pacific Ocean basin region has reverted back to the negative phase of the PDO.

Recently, Vimont and Kossin (2007) (and Kossin and Vimont, 2007) found a strong correlation in the North Atlantic between accumulated cyclone energy (which is positively correlated with tropical cyclone activity) and the Atlantic Meridional Mode (AMM). In their work, they also find that the Atlantic Multi-decadal Oscillation (AMO) may excite the AMM on a decadal time scale. Thus, these indexes, which quantify the climatological background state, correlate with tropical cyclone activity on the decadal time scale (AMO) or both the interannual and decadal (AMM) time-scales. Additionally, interdecadal variability as related to the PDO in the tropical and mid-latitude background climatological state have also been demonstrated in other studies (e.g., Deser et al. 2004, 2006, and Deser and Phillips 2006), and several studies have discussed the synergistic relationship between oceanic and atmospheric conditions needed for an active tropical season (e.g., Zuki and Lupo 2008).

Thus, the goal of this work is three-fold. The first is to examine Atlantic Ocean basin hurricane activity from 2000 – 2007 and place it into context with respect to the earlier work of LJ00. In performing this analysis, the 2005 hurricane season provides a case study, and a rationale for the excessive activity is given. The second is to re-analyze Atlantic Ocean basin activity published in LJ00. Some changes in the classification of ENSO years have taken place recently since the publication of LJ00 (e.g., 1974 has been re-classified as a La Niña year, see the Center for Ocean and Atmospheric Prediction Studies (COAPS, http://www.coaps.fsu.edu), as well as changes in the classification of some hurricanes (e.g., Andrew, 1992, was reclassified as a category 5 storm). While it is hypothesized that these changes would not make substantial changes in the LJ00 climatology, an update is necessary to preserve the integrity of the previously published results. Lastly, the methodologies of LJ00 were applied to hurricane activity in the East Pacific Ocean Basin, as a similar comprehensive study of East Pacific Ocean hurricane activity, including a partition of the hurricane activity into sub-basins, is not available elsewhere. Additionally, an analysis of tropical storm activity for both basins following Schultz (2007) is added here.

2. Data and Methods

The data and methods are similar to those used by LJ00, and more detail regarding some of these subjects can be found there and in references therein. Thus, only a brief review is given here and differences between this study and LJ00 will be highlighted.

2.1 Data

The tropical cyclone occurrence and intensity data (1938 through 2006 – Atlantic, 1970 though 2006 – East Pacific) were downloaded via the UNISYS website (http://weather.unisys.com), and these data can also be found in other archives (e.g., LJ00). A complete description of these data sets and their reliability (e.g., Landsea 1993) can be found in Jarvinen et al. (1984) for the Atlantic, and Davis et al. (1984) for the East Pacific. In this study, we use the term tropical cyclone to include both hurricanes and tropical storms. LJ00 did not include tropical storms in their analysis, and here tropical storms refer only to those entities that obtained maximum wind speeds between 35 – 64 kt. Tropical cyclone data in the Atlantic basin before 1938 were not used in the study as explained in LJ00, and following their lead, this study only uses Saffir-Simpson (Simpson 1974) hurricane intensity data. In order to eliminate problems with some of the data as discussed in LJ00, we combined hurricane intensity categories (category 1 and 2 - weak; category 3, 4, and 5 – intense) following Landsea (1993). The use of the Saffir-Simpson intensity scale precluded the use of tropical cyclone information prior to 1970 in the East Pacific basin since before this date, most storms were simply assigned as a category 1 (e.g., see Schultz 2007).

2.2 Methodology

The complete archive for the years discussed above for the Atlantic Ocean Basin (Fig. 1a) and the East Pacific Ocean Basin (Fig. 1b) were examined in this study. 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., Neter et al. 1988). 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 sub-period as the observed frequency. It has been hypothesized that using the climatological frequency as the "expected" frequency is more appropriate than using an approximated distribution since such analytical distributions (e.g., Poisson distribution) may not adequately represent real-world distributions (e.g., Lupo et al. 1997; LJ00). 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., Lupo et al. 1997; LJ00).

Finally, the data were stratified by calendar year since the nominal tropical cyclone season is recognized as starting on 1 June and ending on 30 November (15 May and 31 October) in the Atlantic (East Pacific) Ocean basin. We then analyzed the annual and monthly distributions of tropical cyclone occurrence in order to find both long and short-term trends in season length within both the total sample and each intensity category. The sample was also stratified by sub-basin in the Atlantic Ocean basin following LJ00. The East Pacific Ocean basin was stratified into quadrants divided by 125° W and 20° N. Hurricanes (tropical storms) were assigned to the basin in which they first reached hurricane (tropical storm) status.

2.3 El Niño and Pacific Decadal Oscillation Definitions

As in LJ00 and references therein, the Japan Meteorological Agency (JMA) ENSO Index was used in this study. A list of El Niño (EN), La Niña (LN), and Neutral (NEU) years used here is displayed in Table 1. In addition to consulting LJ00, a more detailed description of the JMA ENSO Index can be found on the COAPS website. In summary, the index uses 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., Pielke and Landsea 1999). 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. These thresholds are also similar to those used by Schultz (2007) for his study of East Pacific hurricane activity. The JMA ENSO criterion defined the El Niño year as beginning on 1 October of the previous year. This definition, however, was modified following LJ00 so that the El Nino year coincided with the Atlantic and East Pacific hurricane seasons.

The PDO (also known as the North Pacific Oscillation [NPO] in some studies) is a 50 to 70 year oscillation recently described (e.g., Minobe 1997; Mantua et al. 1997) within the eastern Pacific Ocean basin. As defined by Gershanov and Barnett (1998), the positive (warm) phase of the PDO (Fig. 2) is characterized by an anomalously deep Aleutian Low. Cold western and central north Pacific waters, warm eastern Pacific coastal waters, and warm tropical Pacific waters also characterize this phase of the PDO. Following LJ00 this phase is referred to as PDO1. The reverse conditions characterize the negative (cool) phase of PDO (Fig. 2) and these conditions are referred to as PDO2 (e.g., LJ00). Each PDO period, or era, is defined using calendar years (see Table 2) and this information can also be found in Gershanov and Barnett (1998) and Lupo et al. (2007).

Landsea (1993), Gray et al. (1997), and Landsea et al. (1999) have demonstrated that hurricane activity is tied to changes in the long-term pressure patterns in the Atlantic Ocean basin (e.g., the North Atlantic Oscillation, or NAO). Deser et al. (2004) also demonstrate that sea level pressure and other background variables (e.g., wind shear) have displayed interdecadal variations, and Vimont and Kossin (2007) correlate these to Atlantic tropical cyclone activity. LJ00 found that the influence of the PDO was manifested by changes in the ENSO-related variability, specifically, that there was little or no ENSO related variability during PDO2, and significantly fewer and less (more and more) intense hurricanes during El Niño (La Niña) years during PDO1. As stated by LJ00, the NAO-related variations in tropical cyclone activity can make interpretation of PDO-related hurricane variability more difficult given the overlap in the time scales between the PDO and long-term variations in the NAO. Many studies have speculated that these decade-to-decade variations in Atlantic hurricanes are forced by a combination of both. However, no studies separating hurricane activity by phase of the PDO have been performed on East Pacific Ocean basin hurricane activity as of yet, and it is hypothesized here that the relationships described in this paragraph would be the opposite of those found in the Atlantic Ocean Basin. Our hypothesis is based on the spatial pattern of the relative warmth of the Eastern Pacific SSTs for each phase of the PDO as described above (and shown in Fig. 2). This hypothesis is similar to that of the correlation of the ENSO phase with this region’s tropical cyclone activity (see Shultz, 2007 and others).

3. Atlantic Ocean Basin Hurricane Activity Revised and Extended to 2000 - 2007

As stated in the introduction, there have been some changes to the original data sets used by LJ00. Additionally, the latest seven hurricane seasons have been added since the original publication of LJ00, and tropical storm information is included here. Thus, since this work is partially an update of LJ00, this section will focus only on major changes in the Atlantic basin climatology since LJ00, as well as the most recent activity.

3.1 Atlantic hurricane activity: 2000 – 2007

During the 2000-2007 tropical cyclone seasons, there were 62 Atlantic hurricanes, which means that the years since the LJ00 study were the most active during the 1938 – 2007 record. However, the Atlantic tropical cyclone seasons since 1995 have been relatively active. During the six year period from 1995 – 2000, there were 49 hurricanes (81 tropical cyclones), while during the years from 2001 – 2006, there have been 47 hurricanes (94 tropical cyclones), in spite of the fact that 15 hurricanes occurred during the 2005 season. Two other six-year periods were compared to these two recent eras and both of these earlier periods occurred before the satellite era. In particular, 43 (37) hurricanes and 62 (74) tropical cyclones occurred from 1884-1889 (1932-1937). Thus, it would be reasonable to consider the activity of the pre-satellite era periods as comparable to the modern eras, since it is likely that some tropical cyclones were missed during the pre-satellite era.

Additionally, during the 2000 – 2007, there were 29 intense hurricane (category 3 – 5), which represented 47% of all storms (Table 3). This compares with the LJ00 study in which 42% of all storms were intense during the previous 62 years. This indicates only a slight increase in the ratio of intense storms overall. The increased activity of the latest period, however, is less than 50%, which was the number of intense storms for the 30-year period of 1940-69 (Table 3). Thus, as shown in Tables 3 and 4 for the entire 69-year record, the inclusion of the last seven years does not make any noteworthy change in the ratio of hurricane intensities for the overall Atlantic Ocean basin activity. The addition of tropical storm data does not significantly change the overall results of LJ00 either.

3.2 Trends and interannual variability

LJ00 reported that there were no statistically significant trends in the Atlantic Ocean basin hurricane activity. Adding the 2000-2007 hurricane and tropical storm occurrences does not result in any change in the trends for the occurrence of category 2 – 5 storms, in that none of these trends were statistically significant (not shown) at the 95% confidence level. The trend in tropical storms and category 1 hurricanes (not shown) would show an increase stronger than that in Fig. 3, which shows the overall trend for the total number of hurricanes (significant at the 90% confidence level). Whether this upward trend is real is clouded by two issues. The trend could be the result of 1) the problem of the "fortuitous" placement starting and ending points in a long time series (the recent activity could be the peak in a long-term oscillation), or 2) that the earlier part of the 69-year period was in the pre-satellite era and storms may have been undercounted. It is likely that both of these factors are contributing to the overall increase. Nonetheless, if the 1970-2007 period only was used, there was an increase in the occurrence of Atlantic basin tropical storms and category one hurricanes and the trends were also statistically significant (not shown) at the 95% confidence level. However, an examination of Fig. 3 suggests significant interannual variability as found by LJ00.

The addition of the 2000-2007 hurricane occurrences and tropical storm activity did not impact greatly the overall results presented by LJ00 in terms of where these storms occur and their interannual variability (Table 5). Only the Gulf region was slightly more active when considering tropical storm occurrences, and there were a few more western Atlantic tropical storms during La Niña years. The interdecadal variability with respect to the PDO is likewise unchanged by the addition of tropical storm data (Table 6), since there were not significant year-to-year variations in the tropical storm numbers. PDO2 years are marginally more active than PDO1 years, which LJ00 attributed to weaker and less frequent El Niño events. Also, the strong ENSO-related variations in total tropical cyclone numbers during PDO1 years is still a feature found in this study when tropical storms were added to the data set.

3.3 The active 2005 hurricane season, a case study

Of all the years in the Atlantic Ocean Basin, 2005 was the most active. This is likely the result of the convergence of several factors which were favorable for the occurrence of Atlantic hurricanes. Tropical SSTs were warmer than normal within the key regions of the Atlantic (see Fig. 4). We also note here that during the 2005 hurricane season, the tropics experienced the strongest easterly phase of the Quasi-biennial Oscillation (QBO) in recent decades (Fig. 5). The easterly phase QBO has been found to be correlated favorably to increased Atlantic hurricane activity (e.g. Gray, 1984a,b, Elsner et al., 1999) in the past. Recently, the QBO has been found not to correlate well to Atlantic hurricane activity, or at least not to enhance or inhibit it in La Niña years (e.g., The Tropical Meteorology Project - TMP - http://hurricane.atmos.colostate.edu/forecasts/; and Ricks et al. 2007). Nonetheless, due to the decreased upper tropospheric wind shear over the Atlantic basin during the heart of the 2005 hurricane season, the upper level winds were favorable for supporting tropical cyclones (see TMP site). The warmer SSTs and the QBO phase information can be found by accessing the monthly Climate Prediction Center (CPC) Climate Diagnostics Bulletin (see http://www.cpc.ncep.noaa.gov) published in hard copy by the National Centers for Environmental Prediction (NCEP). Finally, 2007 was a year with La Niña-type SSTs (but was not classified as a La Niña year by COAPS), and that would be expected to weaken the Atlantic Ocean basin subtropical trough during that year as well (not shown). Recall, La Niña years were more active overall in the Atlantic (Table 4). A strong subtropical Atlantic trough has been shown to correlate with decreased hurricane activity because of the increased wind shear over the Atlantic (e.g., Goldenberg and Shapiro 1996). Strong wind shear is not favorable to tropical development.

4. East Pacific Ocean Activity: 1970 - 2007

4.1 Climatology and Long Term Trends

Including tropical storms, there were 619 East Pacific tropical cyclone events included in the 38-year sample. This resulted in an average of 16.3 tropical cyclones per season (Table 7). This includes 276 tropical storms (7.3 per year) and 343 hurricanes (9.0 per year). As expected, the number of category 1 storms was the largest (120), and there were 159 intense storms (category 3-5), which represented 46.3% of the hurricane activity. This compares to 42.7% overall in the Atlantic Ocean basin overall.

The overall trend demonstrates that there was a decrease in the East Pacific Ocean (Fig. 6). However, this trend was not statistically significant. This overall trend was opposite to the Atlantic basin where there was a statistically significant increase in activity, but for the combined basins this means there was no statistically significant trend upward or downward. It is noted here that trend lines shown in Fig. 3 and Fig. 6 are simple linear best fit (regression) models. The two time series (from 1970 for the Atlantic region) correlated to each other negatively (correlation coefficient of -0.35, significant at the 90% confidence level), and this will likely be explained by the interannual variability in hurricane activity for both basins being opposite one another as discussed below. An examination of the trends in each East Pacific hurricane category would demonstrate that only the category 3 (5) storms showed a significant downward (upward) trend, while the rest of the categories showed no significant trend.

A breakdown by month (Table 8) indicates that May is the first month that significant tropical cyclone activity begins in the East Pacific. August was the most active month with 152 total storms occurring over the 38 year climatology (4 tropical cyclones per year), and by November, this region is relatively inactive. Thus, the East Pacific season was roughly one calendar month ahead of the Atlantic season, a result similar to Davis et al. (1984) and Schultz (2007). By geographic region (Table 9), the southeast part of the East Pacific was the most active, and 76% (82%) of the hurricane (tropical storm) occurrences happen within this region. Only five tropical cyclones, including two hurricanes occurred in the northwest region.

4.2 ENSO and PDO Variability

During El Niño years, there were more tropical cyclones in the East Pacific (Table 7), and this included more storms reaching hurricane strength, especially intense hurricanes, in this region than in La Niña years. This might be expected as the waters in the East Pacific are warmer during El Niño years. While the greater overall frequency of El Niño year tropical cyclones is not statistically significant, it is opposite of the ENSO variability in the Atlantic Ocean basin.

When separating by PDO phase (Table 10), it can be shown that there was little overall ENSO variability in PDO2 years, while the ENSO variability was accentuated in PDO1 years (two more hurricanes and four more tropical cyclones overall during El Niño years) as it was in the Atlantic region (LJ00), except here El Niño years were more active (a result significant at the 90% confidence level). These were years characterized by stronger warm ENSO SST anomalies located closer to the Americas (see Lupo et al. 2007), or over the East Pacific region, especially the southeast portion of our basin of study. This provided the rationale for the breakdown of the East Pacific Region into sub-basins.

In order to determine if there were variations in the intensity of storms, LJ00 used histograms and compared their distributions, testing these for statistical significance. For the overall East Pacific sample, there were no significant differences in the distributions (Fig. 7), even though the differences in the hurricane frequencies (Table 7) demonstrate that there were differences in the overall averages for the occurrence of intense storms. During PDO2 (there was little ENSO-related interannual variability), and PDO1 (EN years significantly more active), the results were different even if there were no statistically significant differences in the distributions (which can be inferred from Table 10). There were clearly more intense storms during El Niño years (5.0 versus 2.8 for La Niña and 1.8 for Neutral years) for PDO2 years. However, the real substantive differences between hurricane occurrences in El Niño and La Niña years during PDO1 were the result of a greater number of weaker hurricanes and tropical storms. The PDO1 result is consistent with the results of Schultz (2007), who used a different methodology but found that during more active years, there were a greater number of weaker storms. This is, however, different from LJ00, who found that in the Atlantic there were more intense storms during La Niña years, especially in the PDO1 phase.

Comparing the length of the East Pacific season by examining the monthly occurrence (Table 8), shows that during El Niño years, tropical cyclone activity is greatest from May through November, while in La Niña years, the season is shorter (primarily June – October). The seasonal variations in tropical storms versus hurricanes were similar overall. However, the seasonal peak in each ENSO phase occurred in different months. During El Niño years, the peak in tropical cyclone activity was clearly August, while in neutral years the peak was later (August / September), and earlier (July / August) in La Niña years. There was little difference in the ENSO-related seasonal cycles between the phases of the PDO here (not shown).

A breakdown of tropical cyclone activity by geographic region demonstrated that the southeast region was the most active, and varied similarly to that of the total sample discussed above. The northeast region, however, was relatively more active in La Niña and neutral years, while the southwest region was more active in El Niño and neutral years (Table 9). During the El Niño years, this reflects the fact that warmer SSTs were located over the East Pacific formation regions (see Lupo et al. 2007), especially in the southern sectors. While nearly all of the intense hurricanes were in the southwest and southeast regions, neither region had a significantly higher proportion of category 4 and 5 storms. Only one hurricane which formed north of 20^{o} N achieved category 3 status. A separation of these data by phase of the PDO (not shown) would reveal that the ENSO variability described above is independent of the phase of the PDO in the East Pacific.

5. Discussion

5.1 Climatology

As a result of this work, it was shown that by extending the results of LJ00, there was little change overall in the climatology of the Atlantic Ocean basin hurricane activity. By examining the active 2005 season, it was shown that several factors known to correlate with increased hurricane activity in the Atlantic Ocean basin were favorable during that hurricane season. Thus, this very active season can be explained using traditional analyses and the convergence of favorable atmospheric and oceanic processes (e.g., Zuki and Lupo 2008) without necessarily invoking climate change as the cause of the active season. However, it is conceded that climate change as a factor cannot be ruled out as changes in climate could be reflected in the background atmosphere and oceanic conditions which give rise to tropical cyclone formation. Also, it is likely that, while this season was quite active, the disparity in the numbers between 2005 and the next most active year, 1933, was probably not as great as the observed numbers (27 versus 21) due to the lack of satellite observations early in the record. Additionally, the final conclusion of LJ00 was that the next few years after 1999 would be more active hurricane seasons in a manner similar to that of the 1940s through 1960s. Table 3 verifies their assertion of a more active 2000-2007 period. During these eight years, only during the 2002 and 2007 seasons were there few hurricanes and 2002 was an El Niño year. However, there were more tropical storms than a typical year during these seasons. Thus, the work of LJ00 successfully projected long-term increases in hurricane activity.

In the East Pacific, El Niño years were more active hurricane seasons, which implies that SSTs may have been a stronger factor than the atmospheric background state in the interannual variability of the occurrence and intensity of hurricanes in this area of the world. This may be especially true during PDO1 years. This also implies that East Pacific hurricane activity has an inverse correlation to Atlantic Ocean basin activity and, thus, to the QBO. However, the atmosphere may also be more conducive to East Pacific hurricane activity during El Niño years. Zuki and Lupo (2008) demonstrate that a favorable atmospheric background state is an important factor in seasonal tropical cyclone occurrence and that warm SSTs by themselves will not guarantee an active season.

5.2 Hindcasting the 2000-2005 seasons

When forecasting (and hindcasting) hurricane activity in each basin for the upcoming season (Table 11) from 2000-2007 in a manner similar to that demonstrated by LJ00 for 1999, it is shown that this work can be used to produce reliable forecasts. Since a forecast of the geographical distribution of storm genesis regions was given using their method, we evaluated the forecast using the same calculation used to determine χ^2 for the statistical test (Neter et al. 1988). Thus, a lower score represents a better forecast, or shows an annual distribution closer to that of the climatological contingency forecast used by LJ00. The years 2000 – 2005 presumed that the forecast of the ENSO phase was correct as LJ00 did for 1999. In the Atlantic, the poorest hindcast was that for the 2005 season, in which every basin was quite active and, thus, large errors in hurricane occurrence were recorded in each category. However, an active year did not guarantee a high score as the 2003 and 2004 seasons were similarly active, but the hindcast for the 2004 season was much better. In the East Pacific, the hindcasts were better overall and this is likely due to the fact that the southeast region dominates the activity in this basin. Thus, the threshold for what constitutes a good forecast should probably be lower in this region, and several more years would be needed in order to establish a recommendation.

For each of these years, the ratio of tropical storms, weak hurricanes, and strong hurricanes was similar to what should be expected (Tables 6 and 10). This would result in a forecast of a decreasing frequency in each category of stronger winds, except for PDO2 El Niño years in the East Pacific region where more strong storms than weak storms are expected. In the

Atlantic, only 2004 did not conform reasonably to the expected intensity distribution (we observed 3 weak hurricanes and 6 strong). In the Pacific and for each of these years, intensities were reasonably hindcast (not shown).

5.3 Forecasting the 2006 – 2007 seasons

For the 2006 and 2007 seasons, a true forecast was made in January and February assuming that the 2006 and 2007 seasons would be a La Niña-type season based on the SSTs (see Lupo et al. 2007, their table 1). A weak El Niño SST pattern set in during the late summer-to-early autumn during the height of the 2006 hurricane season. The 2007 season was predicted to be a La Nina year. In the Atlantic, the 2006 and 2007 forecasts were still fairly good compared to the previous years, and this is likely due to the fact that during PDO2 years, the distribution of tropical cyclones was fairly similar across each phase of ENSO. The distribution of the tropical cyclone intensities (2006: five TS, three weak, two strong hurricanes; 2007: ten TS, three weak, and two strong hurricanes) was also similar to the expected (five TS, four weak, and three strong hurricanes).

In the East Pacific, the 2006 forecast was better than three of the previous hindcasts, but worse than the other three. Conversely, the 2007 forecast was not very good even though the overall number of storms was close to what would be expected. There were more (fewer) tropical cyclones in the southwest (southeast) part of the East Pacific basin than expected. The 2006 tropical cyclone intensity forecasts for this region (seven TS, five weak, three strong) was somewhat good, except that there were more strong storms observed (eight TS, five weak, 6 strong) than expected. In 2007, the intensity forecasts were better, even if the overall numbers were lower (10 TS, three weak, one strong) Thus, 2006 and 2007 were not as well forecast as most of the hindcasts shown in Table 11. The 2007 forecasts for both regions were similar to that of 2006, since weak El Niño conditions collapsed in February, 2007 and neutral to La Niña conditions could reasonably be expected to develop (Fig. 8).

6. Summary and Conclusions

The climatological behavior of tropical cyclone activity in the Atlantic and East Pacific Ocean basins was examined using the methodologies of LJ00. In the Atlantic, an update to include the 2000 – 2007 seasons, as well as a re-categorization of hurricanes (e.g., Andrew – 1992) or ENSO years (e.g., 1974 becomes a La Niña year) was included. Tropical storm activity was also added to the Atlantic database. In the East Pacific, a thorough breakdown of the hurricane and tropical storm activity from 1970 – 2007 was examined in a manner similar to LJ00.

The major findings for East Pacific tropical cyclone activity demonstrated that there were 16.3 storms per year (9.0 hurricanes and 7.3 tropical storms) which was a greater amount of activity than found in the Atlantic Ocean basin. The long term trend showed only a slight decrease (not statistically significant) in East Pacific tropical cyclone activity, and this was opposite to that of the Atlantic which showed a statistically significant increase. The combined basin trend was not statistically significant, so that either trend for these basins is equally likely. There was a slightly higher percentage of intense hurricanes in the East Pacific than in the Atlantic region, even though there were a few more intense hurricanes in the Atlantic region during 2000 – 2007 than that found in LJ00. The southeast part of the East Pacific ocean basin was the most active, and the seasonal activity (season beginning, peak, and end) was about 15 to 30 days earlier than that in the Atlantic Ocean basin.

An examination of the interannual variability demonstrated that there were more East Pacific tropical cyclones during El Niño years, and that this was mainly accounted for by more storms becoming intense hurricanes than during La Niña years. The tropical cyclone season was one or two months longer in El Niño years, while more storms formed in the southeast and southwest part of the East Pacific Ocean basin. This is likely due to the fact that ENSO years bring warmer waters to the East Pacific region. When breaking down the ENSO years by phase of the PDO, the ENSO-related differences in occurrence and intensity and geographic formation region are accentuated in PDO1 years, but were blurred in PDO2 years. This ENSO and PDO related variability is similar to that occurring in the Atlantic (LJ00), except that in the Atlantic more storms occurred in La Niña years and they were more intense.

Additionally, it is hypothesized here that the Atlantic hurricane season of 2005 was so active not only because of the recent increase in hurricane activity which may be associated with the PDO, but also possibly due to decreased upper tropospheric shear over the Atlantic which may have been associated with a stronger easterly phase of the QBO along with warmer than normal SSTs.

Finally, it is shown that this work may have some forecasting utility by using the same hindcasting method of LJ00, except here we assign each season from 2000 – 2005 a forecast score based on a statistical distribution calculation. This approach included assuming that the ENSO forecast was correct. While the hindcasts for most of these years were reasonable, more seasons will be needed in order to evaluate what would constitute a good score in each basin. Two true forecasts were made for the 2006 and 2007 seasons; and in the Atlantic, the forecasts were relatively good. In the Pacific, the tropical cyclone season forecasts were relatively poor, which may have been due to a poor ENSO forecast in 2006. This work, however, is preliminary and data from additional seasons will be used to verify our approach.

7. Acknowledgements

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8. About the Authors

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Table 1. A list of years examined in this study separated by ENSO phase. The current year is in parenthesis and is not officially classified yet.

La Niña (LN)	Neutral (NEU)	El Niño (EN)
1938	1939	1940
1942	1941	1951
1944	1943	1957
1949	1945-1948	1963
1954 - 1956	1950	1965
1964	1952 – 1953	1969
1967	1958 – 1962	1972
1970 - 1971	1966	1976
1973 - 1975	1968	1982
1988	1977 – 1981	1986 – 1987
1998 - 1999	1983 – 1985	1991
(2007)	1989 – 1990	1997
	1992 – 1996	2002
	2000 – 2001	2006
	2003-2005	

Table 2. Phases of the Pacific Decadal Oscillation (PDO) since 1933.

PDO PHASE	PERIOD OF RECORD
Phase 1	1933-1946
Phase 2	1947-1976
Phase 1	1977-1998
Phase 2	1999-

Table 3. The mean annual number of hurricane and tropical storm (TS) events within the Atlantic Ocean Basin over decadal time periods corresponding with similar studies. Hurricanes are stratified by weak hurricanes (Cat. 1 and 2), intense hurricanes (Cat. 3, 4, and 5), and Cat. 4 + Cat. 5. Categories are based on the Saffir-Simpson scale.

category	1940-69	1970-89	1990-99	2000-07	All
TS	3.7	4.3	4.5	7.9	4.4
Cat. 1,2	2.9	3.4	3.8	4.1	3.4
Cat. 3-5	2.9	1.6	2.6	3.6	2.5
Cat. 4,5	1.4	0.9	1.4	2.3	1.3
Tot hur.	5.8	5.0	6.4	7.8	5.9
TS+Hur.	9.5	9.3	10.9	15.7	10.3

Table 4. The average annual occurrence of Atlantic Ocean Basin tropical storms and hurricanes versus El Niño / La Niña phase for each Saffir-Simpson category.

	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	11.9	5.4	2.1	1.5	1.2	1.0	0.7	6.5
NEU	10.4	4.2	2.4	0.9	1.4	1.0	0.4	6.2
EN	8.7	3.9	2.2	0.9	1.1	0.4	0.2	4.7
Total	10.4	4.4	2.3	1.1	1.2	1.0	0.4	5.9

Table 5. The average annual occurrence of Atlantic hurricanes (tropical storms) by sub-ocean basin as stratified by ENSO phase. The regions are the Caribbean (Crbn), Gulf of Mexico (Gulf), West Atlantic (W Atl), and East Atlantic (E Atl) sub-basins.

	All	Crbn	Gulf	W Atl	E Atl
LN	6.5(5.4)	1.4 (0.8)	1.2(1.3)	2.9(2.5)	1.1(0.8)
NEU	6.2(4.2)	0.9(0.5)	0.9(1.1)	3.0(1.9)	1.3(0.5)
EN	4.7(3.9)	0.5(0.2)	0.6(1.1)	2.9(1.9)	0.8(0.7)
Total	5.9(4.4)	1.0(0.6)	0.9(1.2)	3.0(2.0)	1.1(0.6)

Table 6. The average annual occurrence of Atlantic hurricanes stratified by ENSO phase and Category (Saffir-Simpson scale) during a) PDO2 (1947 - 1976, 1999-present), and b) PDO1 (1938-46, 1977-98).

a.

	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	12.0	5.4	2.3	1.3	1.2	1.2	0.7	6.6
NEU	10.5	3.8	2.4	0.9	1.7	1.3	0.5	6.7
EN	9.7	4.1	2.3	1.1	1.4	0.4	0.5	5.6
Total	10.9	4.5	2.3	1.1	1.5	1.0	0.5	6.5

b.

	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	10.8	5.2	1.8	1.8	0.8	0.8	0.4	5.6
NEU	10.0	4.4	2.5	1.1	0.9	0.8	0.3	5.6
EN	7.1	3.8	2.0	0.5	0.5	0.3	0.0	3.3
Total	9.6	4.4	2.3	1.1	0.8	0.7	0.3	5.2

Table 7. The mean number of East Pacific tropical storms and hurricanes separated by ENSO phase and intensity (Saffir – Simpson scale) in the East Pacific from 1970 – 2007.

Phase	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	15.1	7.3	3.0	1.7	1.6	1.4	0.1	7.8
NEU	16.4	7.1	3.3	1.7	1.6	2.6	0.2	9.3
EN	16.9	7.3	3.0	1.7	2.1	2.2	0.7	9.7
Tot	16.3	7.3	3.2	1.7	1.7	2.2	0.2	9.0

Table 8. The mean number of East Pacific tropical cyclones (tropical storms and hurricanes) by month from May through December (only two tropical cyclones occurred outside these months and are not included on the table.

	May	June	July	Aug	Sept	Oct	Nov	Dec
LN	0.5	2.0	4.2	4.0	2.6	2.6	0.3	0.0
NEU	0.7	2.3	3.5	3.7	3.9	2.2	0.3	0.1
EN	0.6	1.6	3.5	4.8	3.8	2.1	0.6	0.1
Tot	0.6	2.0	3.6	4.0	3.6	2.0	0.4	0.1

Table 9. The stratification of East Pacific basin tropical cyclone activity (yearly means) by geographic region (along 20^{o} N and 125^{o} W) and ENSO phase.

Phase	NE	SE	SW	NW	Tot
LN	1.0	12.4	1.4	0.3	15.1
NEU	1.1	12.7	2.6	0.1	16.4
EN	0.5	13.3	3.2	0.0	16.9
Tot	1.0	12.8	2.4	0.1	16.3

Table 10. The average annual occurrence of East Pacific hurricanes stratified by ENSO phase and category (Saffir-Simpson scale) during a) PDO2 (1970 - 1976, 1999-present), and b) PDO1 (1977-98).

a.

	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	15.4	7.7	3.1	1.9	1.6	1.1	0.1	7.7
NEU	15.4	8.6	3.0	2.0	0.6	1.2	0.0	6.8
EN	15.8	6.8	2.0	2.0	2.3	2.3	0.4	9.0
Total	15.6	7.8	2.8	2.1	1.4	1.4	0.2	7.8

b.

	All	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	T_{hur}
LN	14.0	6.0	2.5	1.0	2.0	2.5	0.0	8.0
NEU	16.7	6.6	3.4	1.5	1.9	3.1	0.1	10.1
EN	18.4	8.2	3.8	1.6	2.0	2.2	0.6	10.2
Total	16.8	6.9	3.4	1.5	2.0	2.8	0.2	9.9

Table 11. The annual hindcasts for tropical cyclone frequencies based on the work of LJ00 (for the 2000-2005 seasons), and forecasts (for 2006 – 2007) based on the results shown here. A simple point scoring system (|predicted – observed|) is used here. The table displays the observed value (|difference from observed|). The value in parenthesis beside the total score is a χ^2 score for that season (a lower score is a better forecast, or is a better "fit").

Atlantic Region

Year		Carribean	Gulf	West. Atl	East Atl.		Tot Score
2000		1 (1)	3 (1)	8 (3)	3 (1)		6 (3.30)
2001		4 (2)	2 (0)	8 (3)	1 (1)		6 (4.50)
2002		2 (0)	3 (1)	6 (1)	1 (1)		3 (2.20)
2003		1 (1)	6 (4)	4 (1)	5 (3)		9 (13.20)
2004		1 (1)	2 (0)	6 (1)	5 (3)		5 (5.20)
2005		7 (5)	6 (4)	11 (6)	4 (2)		17 (31.70)
2006		1 (1)	1 (1)	7 (2)	1 (1)		5 (2.30)
2007		2 (0)	4 (2)	7 (2)	2 (0)		4 (2.80)

East Pacific Region

Year		northeast	southeast	southwest	Northwest		Tot Score
2000		0 (1)	15 (3)	3 (1)	1 (1)		6 (3.25)
2001		1 (0)	9 (3)	5 (3)	0 (0)		6 (5.25)
2002		0 (1)	11 (2)	4 (1)	0 (0)		4 (1.64)
2003		3 (2)	12 (0)	1 (1)	0 (0)		3 (4.50)
2004		0 (1)	10 (2)	2 (0)	0 (0)		3 (1.33)
2005		1 (0)	13 (1)	1 (1)	0 (0)		2 (0.58)
2006		1 (0)	16 (3)	2 (1)	0 (1)		5 (2.69)
2007		1 (0)	10 (3)	3 (2)	0 (1)		6 (5.69)

Figure Captions

Figure 1. The maps of a) the Atlantic Ocean Basin (G = Gulf, C = Caribbean, W (E) = West (East) Atlantic), and the b) Pacific Ocean Basin (NW = Northwest, NE = Northeast, SW = Southwest, and SE= Southeast) used in this study and provided by the National Hurricane Center. The heavy lines represent the boundaries between sub-basins used in this study. Their boundaries are outlined in section 2b and LJ00. The diagonal line across Mexico represents a dividing line between the Atlantic and Pacific Basins.

Figure 2. The phases of the PDO as described in the text. SST anomalies are shown in color in accord with the scale shown. The arrows show anomalies in wind speed and direction. Reproduced with permission from the Joint Institute for the Study of Atmosphere and Ocean (JISAO – http://jisao.washington.edu) at the University of Washington.

Figure 3. The annual frequency of hurricane occurrence in the Atlantic Ocean basin for all categories for the period 1938 – 2007.

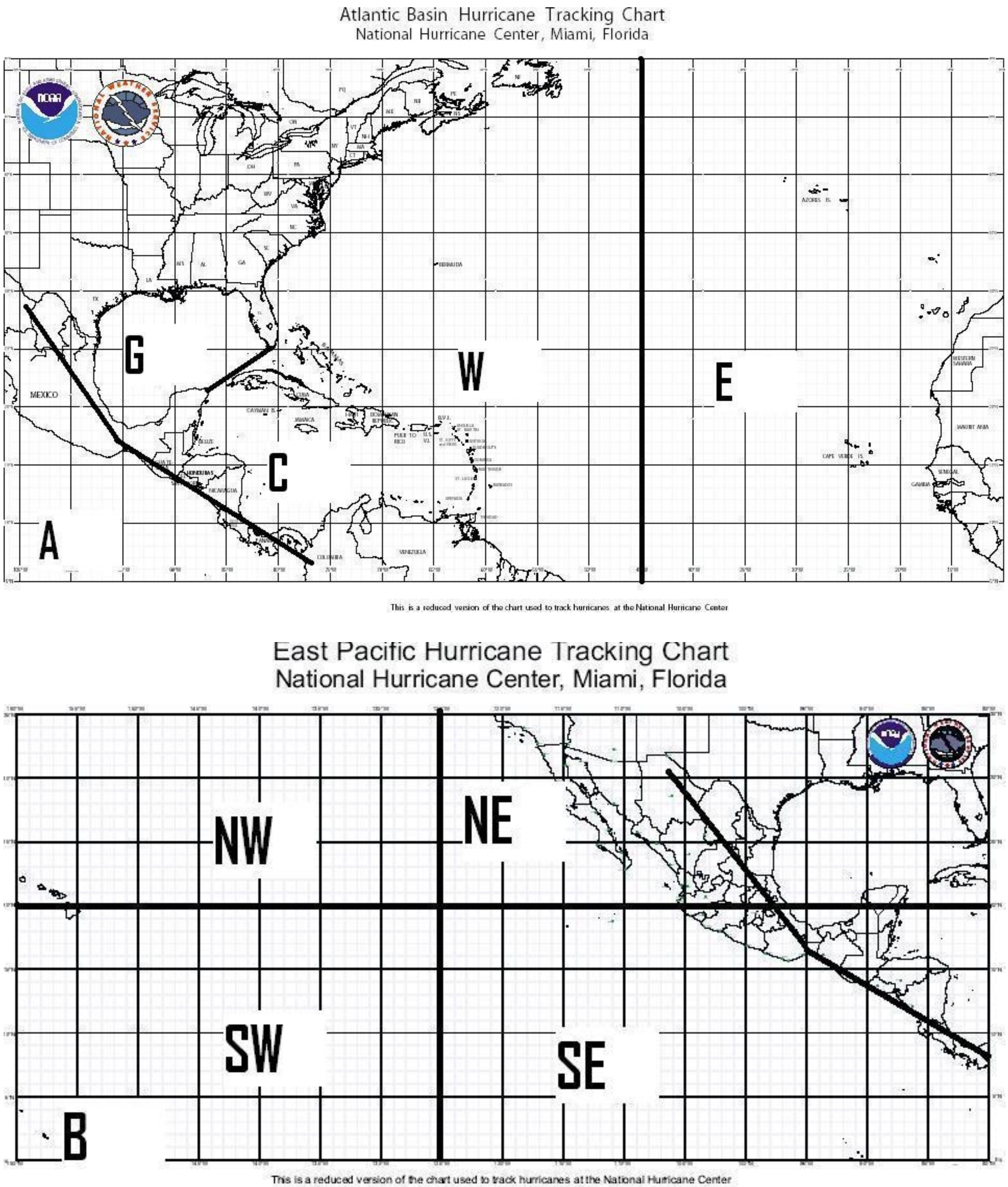
Figure 4. A sample sea surface temperature anomaly (^{o}C) map from the month of September 2005 (source: Climate Prediction Center: Climate Diagnostics Bulletin). The anomalies are relative to the 1971 – 2000 base period.

Figure 5. A time series of 30 hPa (red) and 50 hPa (blue) winds for the tropics (5^{o} N to 5^{o} S) covering approximately a 20 year period (source: Climate Prediction Center).

Figure 6. As in Fig. 2, except for the East Pacific Ocean Basin and the years 1970 - 2007.

Figure 7. Histograms of the average annual hurricane frequency separated by category for a) the total sample, b) El Niño years, c) neutral years, and d) La Niña years.

Figure 8. As in Fig. 4, except for April 2007.

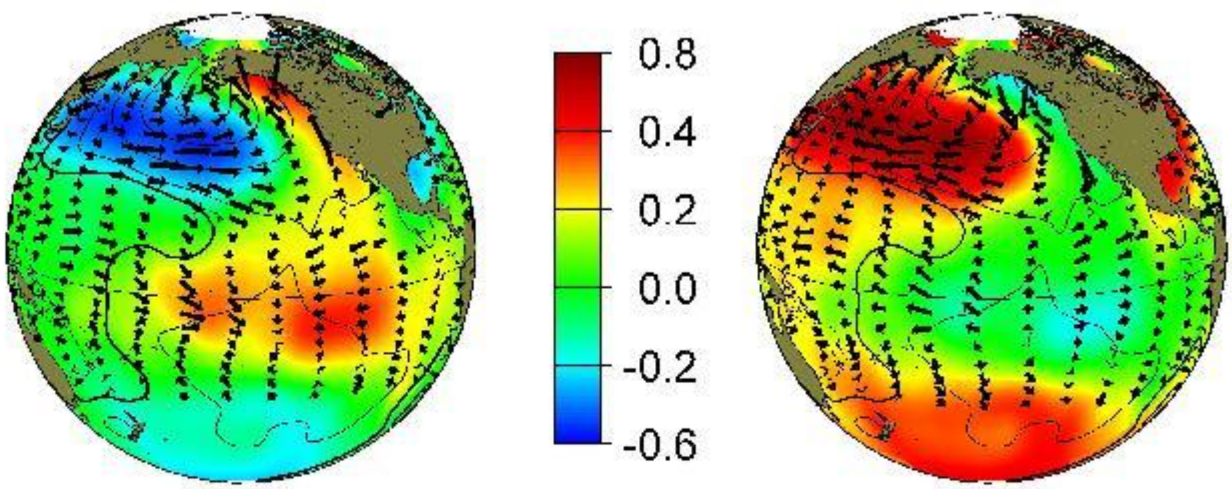


Atlantic Basin Hurricane Tracking Chart
National Hurricane Center, Miami, Florida
G
W
E
MEXICO
C
A
This is a reduced version of the chart used to track hurricanes at the National Hurricane Center
East Pacific Hurricane Tracking Chart
National Hurricane Center, Miami, Florida
NW
NE
SW
SE
B
This is a reduced version of the chart used to track hurricanes at the National Hurricane Center

Figure 1.

Pacific Decadal Oscillation

Positive (warm) phase (PDO1)   negative (cool) phase (PDO2)



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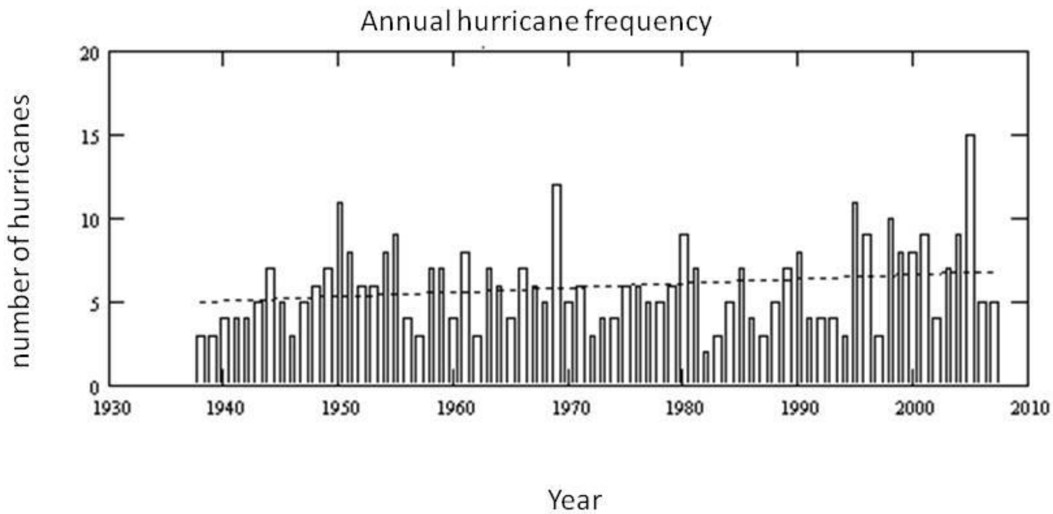

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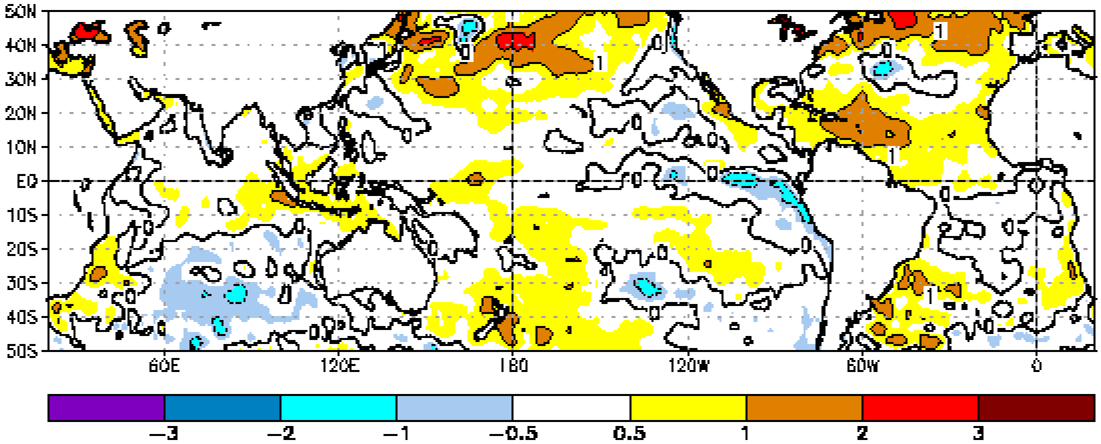

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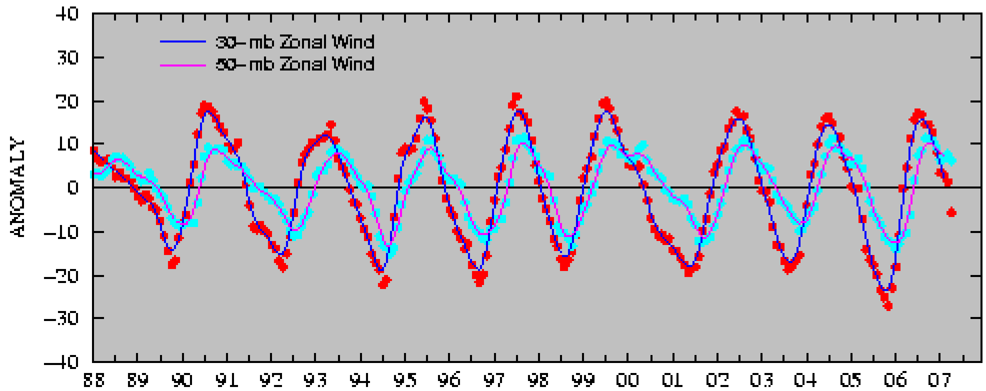

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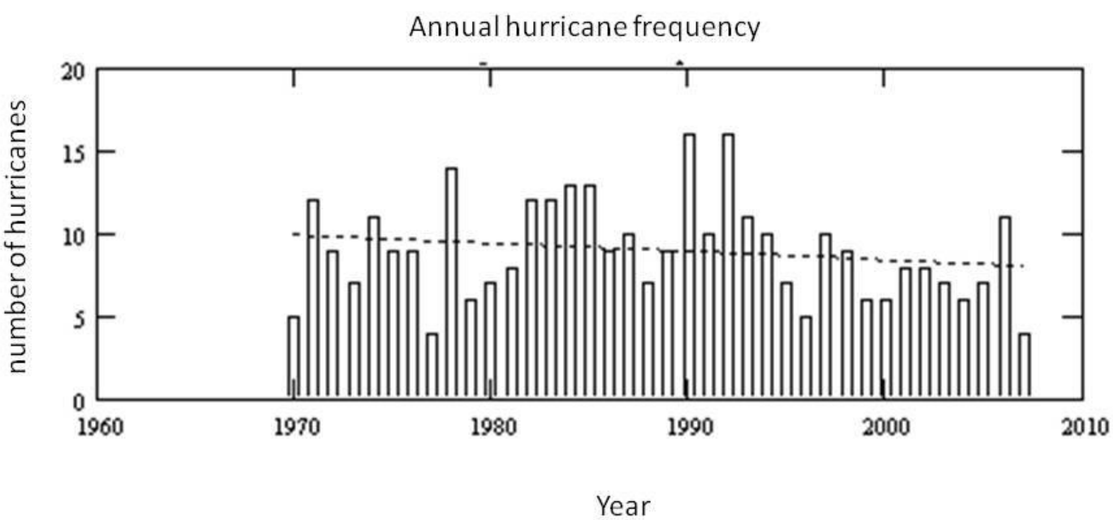

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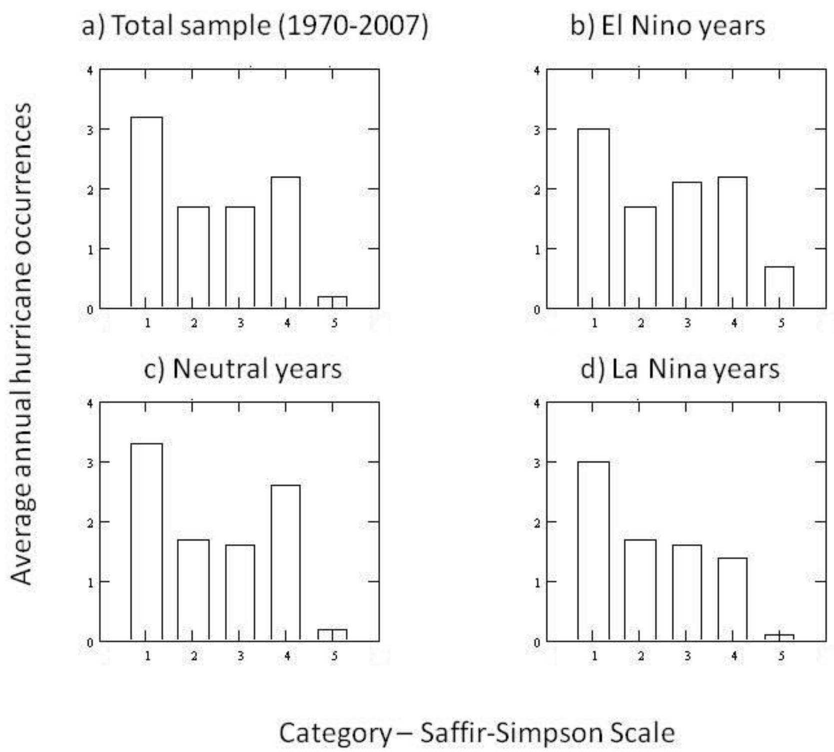

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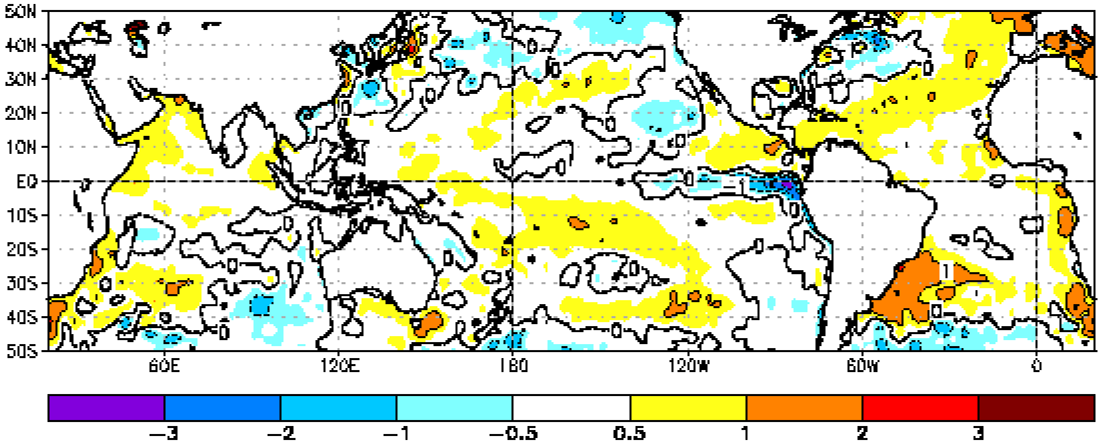

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