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2B.5 THE INTERANNUAL AND INTERDECADAL VARIABILITY IN HURRICANE ACTIVITY OVER THE ATLANTIC AND EASTERN PACIFIC OCEAN.

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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. This interest has been prompted by several active hurricane years in the Atlantic Ocean Basin. This includes the year 2004 in which several storms struck Florida, and the year 2005 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 as related to the El Nino and Southern Oscillation (ENSO). During one phase (negative) of the PDO (1947-1976), they found little ENSO related variability in the number and intensity basin wide. However, during the other (positive) phase of the PDO (1977 – 1999) they found that there was strong interannual variability between El Nino and La Nina years. During La Nina 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 Nina years. Additionally, several studies have shown that since 1999 (see Lupo et al., 2006 and references therein), the Pacific Ocean basin region has reverted back to the negative phase of the PDO.

Thus, the goal of this work is three-fold. The first is to examine Atlantic Ocean Basin hurricane activity from 2000 – 2005 and place it into context with respect to LJ00. In performing this analysis, the 2005 hurricane season provides a case study and a rationale for the excessive activity will be provided. The second is to re-analyze Atlantic Ocean Basin activity published in LJ00. Some changes in the classification of ENSO years have taken place since recently (e.g., 1974 re-classified as a La Nina 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, 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 published results. Lastly, the methodologies of LJ00 were applied to hurricane activity in the East Pacific Ocean Basin, and 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 will be added here.

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2. METHODS AND ANALYSES

The data and methods are similar to those used by LJ00, and more detail regarding some of these subjects can be found there and references therein. This preprint will focus on activity in the Eastern Pacific since there were no substantive changes in the Atlantic region climatology.

2.1 Data

Hurricane occurrence and intensity data (1938 through 2006) were downloaded from the Colorado State University Archive through the UNISYS[1] website. A complete description of this data set, it's uses, and limitations can be found in Jarvinen et al. (1984). Hurricane data before 1938 may be less reliable[2] (e.g., Landsea, 1993) and were not used. In order to provide a dataset that is the less vulnerable to error or bias, this study only uses Saffir-Simpson (Simpson, 1974) hurricane intensity data. Central pressure data were not always available for each storm in the earlier years in the period described above and were not used. Maximum wind data have been shown to contain biases (e.g., 1944 - 1969), or, in many cases especially before 1944, are estimated. Landsea (1993) discusses the 1944 - 1969 bias in maximum wind speeds (as much as 5 kt or 2.5 m s^{-1}) at some length. To reduce the influences of these biases in maximum wind speed, hurricane intensity was assigned based on the maximum Saffir-Simpson intensity attained by the storm. Thus, only storms which reported maximum wind speeds close to the limits of a particular Saffir-Simpson category would be vulnerable to being improperly classified. To reduce this problem even further, many of the results are discussed by combining hurricane intensity categories (category 1 and 2 - weak; category 3,4, and 5 - intense (following Landsea, 1993)).

2.2 Methodology

The entire Atlantic Ocean Basin and the East Pacific Ocean Basin were examined in this study. Other studies limit their region of study to landfalling hurricanes (e.g., Bove, et al., 1998), or to "intense" ("major") hurricanes, usually defined as Saffir-Simpson category 3 storms or higher. Tropical storms were not included in this study since the record for these storms may be less complete than the hurricane record, especially earlier in the period when categorization was not applied to these storms. Simple means and correlations were calculated and analyzed, and these means were tested for significance using a simple two-tailed z-score test, assuming the null hypothesis (e.g., Neter et al., 1988). Intensity distributions were also tested using a Chi-square statistical test. These distributions were tested using the total sample climatology as the expected frequency and a sub-period as the observed frequency. It is 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). 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.

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

2.3 Definitions of El Nino and Pacific Decadal Oscillation

The Japan Meteorological Agency (JMA) ENSO Index was used in this study. A list of El Nino (EN), La Nina (LN), and Neutral (NEU) years (Table 1), as well as a more detailed description of the JMA ENSO Index, can be found by accessing the Center for Ocean and Atmospheric Prediction Studies (COAPS) website[3]. In summary, the index classifies years as EN, LN, and NEU based on 5-month running-mean Pacific Ocean basin sea surface temperatures (SST) anomaly thresholds bounded by the region 4^{o} N, 4^{o} S, 150^{o} W, and 90^{o} W. The defined region encompasses both the Nino 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^{o} C, less than -0.5^{o} C for LN years, and NEU otherwise. For classification as an EN or LN year, these values must persist for 6 consecutive months including October, November, and December. The JMA ENSO criterion defined the El Nino year as beginning on 1 October of the previous year. This definition, however, was modified here so that the El Nino year commenced with the initiation of the Atlantic hurricane season. This modification was necessary since El Nino conditions typically begin to set in before 1 October, and 1 October is close to the climatological peak of the Atlantic hurricane season (10 September).

The PDO (also known as the North Pacific Oscillation [NPO] in some studies) is a longer-term SST oscillation occurring over a 50 to 70 year time period (e.g., Minobe, 1997) within the eastern Pacific Ocean basin. As defined by Gershanov and Barnett (1998), the positive phase of the PDO 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, which we refer to as PDO1. The reverse conditions characterize the negative phase of PDO and we refer to these conditions as PDO2. Each phase of the PDO is described by calendar year (Table 2) and this information can be found in Gershanov and Barnett (1998) and Lupo et al. (2006).

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 (NAO). LJ00 found that the influence of the PDO was manifest by changes in the ENSO- related variability, specifically, that there was little or no ENSO related activity during PDO2, and significantly fewer and less (more and more) intense hurricanes during El Nino (La Nina) years during PDO1. The NAO-related variations in hurricane activity can make interpretation of PDO-related hurricane variability more difficult given the overlap in the time scales between the NPO and NAO. It is likely that these decade-to-decade variations in Atlantic hurricane are forced by a combination of both, and further study on this topic is ongoing. However, no studies have been performed on East Pacific Ocean Basin hurricane activity, and it is hypothesized here that the relationships described in this paragraph would be the opposite that found in the Atlantic Ocean Basin.

Table 1. A list of years examined in this study separated by ENSO phase.

La Nina	Neutral	El Nino
1970 - 1971	1977 - 1981	1972
1973 - 1975	1983 - 1985	1976
1988	1989 - 1990	1982
1998 – 1999	1992 – 1996	1986 - 1987
	2000 – 2001	1991
	2003 - 2005	1997
		2002
		2006

Table 2. A list of years separated by phase of the PDO.

PDO Phase	Period of record
PDO2	1947 – 1976
PDO1	1977 – 1998
PDO2	1999-present

1. These data are available through the UNISYS website. The web address is at: http://weather.unisys.com.

2. Landsea (1993) recommends using 1944 as the start date for reliable data. Data before that may be less reliable since these are pre-aircraft reconnaissance years. 1938 was chosen for this study in order to ensure a sufficiently long sample (60 years or more) that included a greater number of El Nino and La Nina seasons. It is assumed that in the case of 'missed' storms, the error is random.

3. The COAPS website is at: http://www.coaps.fsu.edu

3. ATL HURRICANE ACTIVITY: 2000 - 2006

During this period there were 52 Atlantic hurricanes, which indicates that this seven year period the most active in the entire time series. However, during the six year period from 1995 – 2000, there were 49 storms, while during the years from 2001 – 2006, there have been 47 storms. This is in spite of the fact that 15 storms occurred during the 2005 season. This also compares with two other six-year periods which occurred before the satellite era in which 43 (37) storms occurred from 1884-1889 (1932-1937). Additionally, during the 2000 – 2006, there were 27 intense storms (category 3 – 5), which represented 48% of all storms. 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.

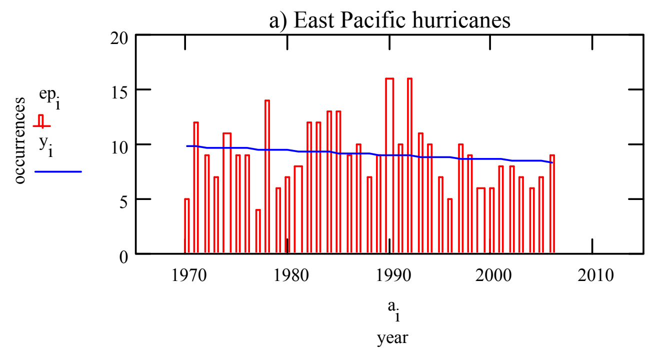
Of these years, 2005 was the most active. It has been demonstrated in many studies (e.g., LJ00) that this decade is a time when hurricane activity has increased. Also, several researchers noted that during the 2004 and 2005 seasons, tropical SSTs were warmer than normal within the key regions of the Atlantic. Finally, we note here that the easterly phase of the Quasi-biennial Oscillation (QBO), which has been noted to be correlated favorably to increased Atlantic hurricane activity (e.g. Gray, 1984) due to the decrease in upper tropospheric shear over the Atlantic basin. The warmer SSTs and the QBO phase can be seen by accessing the monthly Climate Prediction Center Climate Diagnostics Bulletin (see http://www.cpc.ncep.noaa.gov). The QBO peaked in the easterly phase during the hurricane season, and it was the strongest easterly phase in over 20 years.

4. EAST PACIFIC HURRICANES: 1970 - 2006.

4.1 Climatology and Long Term Trends

Including tropical storms, there were 602 tropical cyclone events included in the 37 year sample as of November 2006. This resulted in an average of 16.2 tropical cyclones per season. This includes 264 tropical storms (7.1 per year) and 338 hurricanes (9.1 per year). As expected, the number of category 1 storms was the largest (117), and there were 158 intense storms (category 3-5), which represented 46.7% 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. 1a) overall, however, this trend was not significant at the standard levels of confidence. This is similar to the Atlantic basin where there was a statistically insignificant decrease in activity (Fig. 1b), and for the combined basins means there was no trend. Even though the two time series do not display a statistically significant trend, they do correlate to each other negatively (correlation coefficient of -0.35, significant at the 90% confidence level), and this will likely be explained by an examination of the interannual variability.



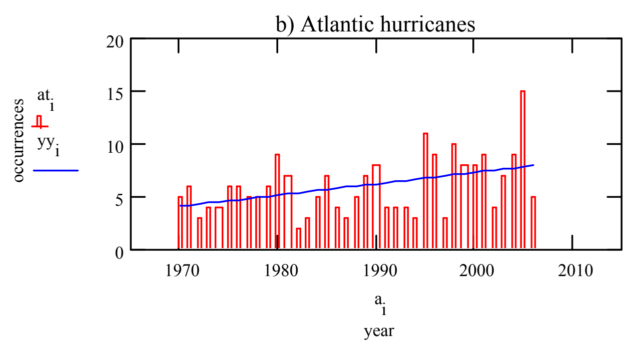


Figure 1. The hurricane activity from 1970 – 2006 for the a) East Pacific Ocean region, and b) the Atlantic Ocean basin.

A breakdown by month indicates that May is the first month that significant tropical cyclone activity begins as there is nearly one tropical cyclone per month. August is the most active month with 148 total storms occurring over the 37 year climatology (4 tropical cyclones per year), while by November, this region is relatively inactive. Thus, the East Pacific season is roughly one calendar month ahead of the Atlantic season. By geographic region, the southeast part of the East Pacific is the most active and 77% (81%) 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 Nino years (nine years), there were more tropical cyclones in the East Pacific (Table 3), and this included more storms reaching hurricane strength, especially intense hurricanes, in this region than in La Nina years (eight years). This might be expected as the waters in the East Pacific are warmer in El Nino years. While this result is not statistically significant, it is opposite of the ENSO variability in the Atlantic Ocean Basin. When separating by PDO phase (not shown here), it can be shown that there is little overall ENSO variability in PDO2 years, while the ENSO variability is accentuated in PDO1 years (two more hurricanes and four more tropical cyclones overall in El Nino years) as it was in the Atlantic Region (LJ00). These were years characterized by stronger warm ENSO anomalies located closer to Americas (see Lupo et al. 2006).

Table 3. The mean number of tropical storms and hurricanes separated by ENSO phase and intensity (Saffir – Simpson scale) in the East Pacific from 1970 – 2006.

Phase	C1	C2	C3	C4	C5	Hurr	TS	Tot
EN	3.0	1.7	2.1	2.2	0.7	9.7	7.3	16.9
Neu	3.3	1.7	1.6	2.6	0.2	9.3	7.1	16.4
LN	3.0	1.9	1.8	1.5	0.1	8.3	7.0	15.3
Tot	3.2	1.7	1.8	2.3	0.2	9.1	7.1	16.2

Comparing the length of the season by examining the monthly occurrence (Table 4), shows that during El Nino years, tropical cyclone activity is greatest from May through November, while in La Nina years, the season is two months shorter (June – October). The seasonal variation of tropical storms and hurricanes were similar overall. However, the seasonal peak of each phase occurred in different months. During El Nino 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 Nina years. There was little difference in the ENSO related activity between the phases of the PDO here (not shown).

Table 4. The mean number of tropical cyclones by month from May through December (only two tropical cyclones occurred outside these months and are not included on the table.

	M	J	J	A	S	O	N	D
EN	0.6	1.6	3.5	4.8	3.8	2.1	0.6	0.1
N	0.7	2.3	3.5	3.7	3.9	2.2	0.3	0.1
LN	0.3	2.3	4.3	4.0	2.4	2.7	0.4	0
Tot	0.5	2.1	3.6	4.0	3.5	2.0	0.4	0.1

A breakdown of tropical cyclone activity by geographic region demonstrated that the southeast region was the most active. The northeast region, however, was relatively more active in La Nina and neutral years, while the southwest region was more active in El Nino and neutral years (Table 5). 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 storm 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 there is similar ENSO variability in both phases of the PDO, but that the results shown in Table 5 are stronger in the PDO1 phase.

Table 5. 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
EN	0.5	13.3	3.2	0.0	16.9
Neu	1.1	12.7	2.6	0.1	16.4
LN	1.0	12.6	1.2	0.4	15.3
Tot	0.9	12.8	2.4	0.1	16.2

5. SUMMARY AND CONCLUSIONS

The climatological behavior of tropical cyclone activity in the Atlantic and East Pacific Ocean basins are examined using the methodologies of LJ00. In the Atlantic, an update to include the 2000 – 2006 regions, as well as all re-categorization of hurricanes (e.g., Andrew – 1992) or ENSO years (e.g., 1974 becomes a La Nina year) was included. In the East Pacific, a thorough breakdown of the hurricane and tropical storm activity from 1970 – 2006 was examined.

The major findings for East Pacific tropical cyclone activity demonstrated that there were 16.2 storms per year (9.1 hurricanes and 7.1 tropical storms) and this was a greater amount of activity than found in the Atlantic Ocean basin. The long term trend showed a slight decrease in East Pacific tropical cyclone activity, and this was similar to that of the Atlantic which showed only a slight increase. Neither was statistically significant, or no trend in each basin is equally likely. There were slightly more intense hurricanes as a percentage in the East Pacific than in the Atlantic region, even though there were a few more intense hurricanes in the Atlantic region during 2000 – 2006 than that found in LJ00. The southeast part of the East Pacific ocean basin was most active, and the seasonal activity was about 15 to 30 days earlier than in the Atlantic Ocean basin.

An examination of the interannual variability demonstrated that there were more East Pacific tropical cyclones during El Nino years, and that this was mainly accounted for by more storms becoming intense hurricanes than during La Nina years. The tropical cyclone season was one – to - two months longer in El Nino years, while fewer storms formed in the northeast and northwest 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 and are 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 Nina years.

Finally, it is hypothesized here that the Atlantic hurricane season of 2005 was so active not only because of the recent interdecadally driven increase in hurricane activity and warmer SSTs, but also due to decreased upper tropospheric shear over the Atlantic due to a stronger easterly phase of the QBO, which has been shown to correlate positively to the occurrence of Atlantic hurricane activity. This will be demonstrated more strongly in future work.

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