The Variability in Atlantic Ocean Basin Hurricane Occurrence and Intensity as related to ENSO and the North Pacific Oscillation

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Abstract

The investigation of the effect of El Niño-related variability on hurricane activity has been a popular topic of study. Studies have shown that there are fewer Atlantic Ocean basin hurricanes during an El Nino year than during a La Nina year. 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. The effect of the El Niño/La Niña cycle on hurricane intensity, however, is not straightforward. Studies addressing the interannual variability of hurricane intensity have captured far less attention than the more generalized subject of hurricane occurrence. This study examined the interannual variability of hurricane intensity (measured as wind speed and interpreted through the Saffir-Simpson Scale) from 1938 through 1999. These data were then compared with the occurrence of El Niño/La Niña events as defined using the Japan Meteorological Association (JMA) index. El Nino/La Nina variability superimposed on variability associated with the North Pacific Oscillation (NPO) 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. There were also significant differences found in hurricane intensity between El Nino and La Nina years when the NPO was in phase 1, rather than when the NPO was in phase 2. Finally, this study also examined the interannual variation in hurricane intensity by genesis region (i.e. the eastern and western Atlantic Ocean Basins, the Caribbean, and the Gulf of Mexico).

1. Introduction

Within the Atlantic Ocean Basin, the year-to-year variability of tropical cyclone occurrence as it relates to the El Nino and Southern Oscillation (ENSO) is now well-established (e.g., Gray, 1984a,b; Gray et al., 1993; and Bove et al., 1998). Aller (1999) discusses the occurrence of 1997 tropical cyclones and relates the "almost complete shut down of Atlantic tropical storm and hurricane activity" to the strong El Nino event that began in mid-1997 and persisting into 1998. Rappaport (1999) also notes the decline in Atlantic hurricane occurrence during 1997 and relates the decline to the presence of El Nino. Gray (1984a,b) discusses factors that either enhance or dampen Atlantic Ocean Basin tropical cyclone activity, and found that during El Nino years hurricane activity in the Atlantic region is suppressed. Gray et al. (1993) then demonstrate that La Nina years are more active hurricane seasons in the Atlantic region. Since the early 1980's, studies (e.g., Landsea and Gray, 1992) have demonstrated a correlation between the long-term variability of rainfall in the western Sahel region and Atlantic hurricane activity (as related to pressure variations in the Atlantic Ocean Basin). These factors, in addition to others such as the Quasi-Biennial Oscillation, are components in the annual hurricane forecasts issued by Dr. William Gray's hurricane forecast team in the Atmospheric Science Department at Colorado State University and the Hurricane Research Division (HRD) (e.g., Colorado State Press Release, 1999). Additionally, these factors influence hurricane occurrence as a result of their impact on the strength of the upper tropospheric subtropical westerlies and, thus, the amount of vertical shear in hurricane formation regions (e.g., Gray 1984a, Shapiro, 1987). Greater amounts of vertical shear are generally considered detrimental to hurricane development, and Goldenberg and Shapiro (1996) identify the subtropics (10^{o} - 20^{o} N) as the region that is most sensitive to variations in vertical shear.

A number of recent studies (e.g., Landsea, 1993; O'Brien et al., 1996; Bove et al., 1998; Landsea et al., 1999; and Pielke and Landsea, 1999) have examined past Atlantic Ocean basin hurricane activity, especially those systems that strike the coast. Landsea et al. (1999) revealed that there has been a decrease in the number of U.S. landfalling hurricanes between 1944 - 1996, with no significant trend in hurricane intensity. Pielke and Landsea (1999) found that during La Nina years there was a tendency toward more intense and damaging hurricanes making landfall on the U.S. coast. Landsea (1993) found earlier that there had been a tendency toward fewer intense hurricanes over a similar time period (1944-1991). This finding parallels a tendency toward fewer landfalling intense hurricanes during the 1970's and 1980's (as compared to the 1940's and 1950's). O'Brien et al. (1996) and Bove et al. (1998) also studied ENSO-related variability with respect to landfalling U.S. hurricanes. They found that there were fewer hurricanes that made landfall along the United States during an El Nino year, and there was a reduced chance for a major hurricane as well. Landsea (1993), Gray et al. (1997), and Landsea et al. (1999) demonstrated that hurricane frequency and intensity follow longer-term cycles than the El Nino-related variability demonstrated above. These studies have linked long term pressure and sea surface temperature trends and oscillations in the Atlantic Ocean Basin to hurricane frequency to enhanced hurricane activity in the 1940's to the early 1960's and decreased activity during the 1970's and 1980's.

The issue of climate change and the dynamic mechanisms leading to climate change on global and regional scales has garnered the attention of the research community as well as the interest of general public (e.g., Houghton et al., 1996, *hereafter IPCC, 1996*) in recent years. The research community has been especially interested in climate change as it relates to the occurrence of extreme or hazardous weather, including hurricanes (IPCC, 1996; Henderson-

Sellers et al., 1998). Various mechanisms have been examined in order to explain long and short-term climate variations, including the effect of increasing CO_2 concentrations, which have been linked ostensibly to human activities (e.g., IPCC, 1996; Singer, 1997). Climatic fluctuations due to natural variability within the earth-atmosphere system have also been examined extensively. In particular, shorter-term variations in local climates, have been linked to coupled ocean-atmosphere phenomena such as ENSO, the North Atlantic Oscillation (NAO) (e.g., Hurrell, 1995; Gray, 1998), and most recently, the North Pacific Oscillation (NPO) (e.g., Gershanov and Barnett, 1998). These phenomena have been shown to influence the mean structure of mid-latitude atmospheric circulations on time scales from seasons (e.g., McPhadden, 1999), to a few years (e.g., ENSO related variability), to decades (e.g., NPO variability). The atmospheric circulations are influenced by the forced response of the atmosphere to sea surface temperatures (SSTs). Thus, these phenomena influence the climatological characteristics of jet streams in the Northern Hemisphere due to their impact on well-known Northern Hemispheric teleconnection patterns (e.g., Wallace and Gutzler, 1981; Hurrell, 1996).

A climatology of Atlantic Ocean basin hurricanes is presented in this study using a database that is available online. The entire region encompasses the Atlantic Ocean, the Caribbean, and the Gulf of Mexico, and this study included all hurricanes that occur within these areas. Annual mean hurricane activity as defined by intensity values was examined in order to find long and short-term trends, and to investigate interannual variability in hurricane occurrence, and its relation to ENSO and NPO variability. Statistical testing was performed in order to determine whether or not these relationships are statistically significant.

2. Data and Methodology

2.1 Data

Hurricane intensity data (1938 through 1999) were downloaded from the Colorado State University Archive through the UNISYS[1] website. These data were compiled by the National Hurricane Center. 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 (follows Landsea, 1993)). The reader is cautioned to be aware that this bias discussed by Landsea (1993) exists and may influence the classification of a few storms in the earlier period. Finally, the maximum intensity was also used rather than an “average intensity” since an “average intensity” would tend to skew the distribution toward the lower categories.

2.2 Methodology

The entire Atlantic Ocean Basin (Fig. 1) was 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. This study endeavors to study the complete hurricane archive provided by Landsea (1993). 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. 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 November 30, and this definition conforms reasonably to the definition of the El Nino/La Nina year used here. 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 with the Atlantic Ocean basin (Fig. 1). The North American and Greater Antilles (e.g., Cuba or Hispanola) coastlines bound the Gulf of Mexico sub-region. The Caribbean Basin was bounded by Central America, South America, and the Antilles. Finally, the Atlantic Ocean was divided into the east and the west Atlantic Ocean basins using the 45th meridian. Hurricanes were assigned to the basin in which they first reached hurricane status.

2.3 Definitions of El Nino and North Pacific 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 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 hurricane season (10 September).

The NPO 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 NPO 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 NPO, which we refer to as NPO1. The reverse conditions characterize the low phase of NPO and we refer to these conditions as NPO2. Each phase of the NPO is described by calendar year (Table 2) and this information can be found in Gershanov and Barnett (1998) and Kerr (1999). Gershanov and Barnett (1998) found a correlation between NPO phase and the intensity of ENSO as they both affect the atmospheric climatological flow regimes over the United States simultaneously. In particular, they find that the NPO serves to either enhance or weaken the ENSO phenomenon, and thus the strength of the influence of the ENSO phenomenon (depending on the NPO phase). During NPO1 (NPO2), the intensity of El Nino and its impacts on North American atmospheric climatological flow regimes and circulation features tends to be greater (weaker), with a less (more) intense La Nina impact.

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). One hypothesis to be tested here is that NPO-related variability will be found when stratifying hurricane characteristics by NPO years. The NAO-related variations in hurricane activity may make interpretation of NPO-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. *It is reasonable, however, to suspect that hurricane activity may be* *correlated to NPO phase as well since NPO has been shown to modulate ENSO intensity, which has been tied to hurricane activity.*

3. Trends and ENSO-related variability

A total of 352 hurricanes were archived, including 134, 69, 73, 53, and 23 events in categories 1 through 5 respectively. This resulted in an average of 5.7 hurricanes and 2.4 intense hurricanes (Category 3,4,5) per season (Table 3), which is consistent with many published values (e.g., 5.8 and 2.2 found on the CSU tropical prediction website). Hurricane activity was noted in every month from May through December, with 85% of the activity occurring from August to October. Intense hurricane activity was even more focused within the hurricane season and almost all category 5 hurricanes (91%) occurred in August and September.

Figure 2 is a histogram showing the 62-year sample plotted with respect to time for the total sample and each category. A regression analysis shows that there was a weak upward trend in the total number of Atlantic Basin hurricanes. There was a stronger upward trend in the number of category 1 storms, but downward or weak trends in all other categories; thus, the stronger trends were masked by the weak overall trend. However, none of these trends proved to be statistically significant. As stated in Landsea (1993) and on the CSU Tropical Prediction website, however, it is difficult to relate these trends to long-term global climate change (e.g., as influenced by increased CO_2 concentrations). A more comprehensive study of this issue was recently published by Henderson-Sellers et al. (1998) and discussion of the issue is beyond the scope of this study.

To examine interdecadal variability in a crude manner, it was useful to average across decadal periods which were relatively more active (Table 3) than others. The decades between 1940 to 1969 averaged 5.8 hurricanes per season, including 6.9 hurricanes annually through the decade of the 1950s. The two decades that followed had averaged 5.0 events per season. The decade of the 1990s has averaged 6.4 events per season; however, this result may be skewed by the very active 1995 and 1996 seasons. There is, nonetheless, an upward trend in the hurricane activity in the 1990s, especially late in the decade. The trends that were found within the preceding decadal periods were also consistent with those described by, for example Landsea and Gray (1992) and Landsea (1993). An examination within each category demonstrates that weak hurricanes (Category 1 and 2) averaged 2.9 per season in the 1940 to 1969 period, and averaged 3.4 events per season in the 1970 - 1989 period. This relatively weak trend was contrasted by the stronger decrease in intense hurricanes (from 2.9 per year to 1.6 per year). Within the decade of the 1990s there was an average of 3.8 weak and 2.6 intense hurricanes per year, suggesting an upward trend again in intense hurricane activity. These data also suggest that there was interannual variability in the data on a longer time-scale than that of the well-known ENSO-related variability, which will be examined in section 4.

Interannual variability in the total number of events and in each category is evident by examining the data shown in Fig. 2. An analysis was performed to examine shorter-term interannual variability as related to the El Nino (EN) / La Nina (LN) cycle. Table 4 displays the number of events and annual means vs. EN / LN phase. During EN years, 4.8 hurricanes occurred on the average comparing with 5.8 and 6.2 for NEU and LN years; respectively, however, these results were not significant at the 90% or 95% level. While there was little difference in the mean number of weak hurricanes across each phase (Fig. 3), there were more intense hurricanes during LN and NEU years (2.7 and 2.5 per year, respectively) than during EN years (1.7 per year). The higher number of intense hurricane events for LN years was not statistically significant at the 90% level (using the z-score test). The distributions in Fig. 3 were also tested for significance using the χ-square test, which showed that the ENSO-related differences described above, are not significant at the 90% level either. Nonetheless, ENSO-related intensity variations became even more dramatic when examining only Category 4 and 5 hurricanes for the LN and EN phases (1.6 vs. 0.7 per year, respectively). Thus, it is possible that the lower number of hurricanes occurring between 1970 and 1990 may reflect the more frequent occurrence of strong EN events, especially during the 1980s. This analysis demonstrates that there is not only a correlation between EN years and reduced hurricane activity (as has been shown in many studies); but also, EN years may be associated with less intense hurricanes as well. Again, as stated in section 1, the occurrence of fewer and weaker hurricanes during EN years is likely, at least in part, the result of the interannual variability of tropospheric wind profiles within the sub-tropical Atlantic Ocean basin.

A monthly analysis of the mean annual hurricane occurrence (Table 5) showed that ENSO-related variability paralleled the total sample (e.g., more hurricanes occurring during LN and NEU years) for each month (especially August through October) during the hurricane season with the exception of June. In June, there were more events occurring during EN years than during LN years. This result may be due to the low frequency of hurricane occurrence so early in the season making ENSO-related variability difficult to discern with certainty. A discernable difference in the length of hurricane season existed between the El Nino and Neutral phases. During EL years hurricane activity picks up (arbitrarily defined here as the first and/or last month in which the average occurrence is 0.25 event per year, or 1 event every four years) in

June and tails off by November. The longest hurricane seasons (June through November) persisted in NEU years. The hurricane season did not start picking up (winding down) until July (during October) during LN years. During the most active part of the hurricane season, there were clearly more hurricane occurrences during LN years than during EN years, and the paucity of EN year hurricane activity in September (August - October) is significant at the 85% (75%) confidence level. Finally, this month-by-month stratification would also show similar results to the total sample with the monthly analysis accomplished with the Saffir-Simpson categorization (not shown here). This is because LN years were associated with more intense hurricane activity. The strongest events depict this the most clearly since, of the 23 category 5 storms that occurred in the total sample, 19 of these occurred during LN (12) or NEU (7) years.

Stratifying the results by sub-ocean basin (Table 6) demonstrated that most hurricanes originated in the western Atlantic Ocean basin (about 3 per year), with an average of one hurricane annually developing in each of the other sub-regions. Within the eastern Atlantic sub-basin there were 33% more hurricane events occurring in LN years as compared to EN years. There was little significant ENSO-related variability in the western Atlantic sub-basin; however, much of the reduction of hurricane activity in the Atlantic Ocean region was a result of the combined reduction (50%) in Caribbean and Gulf storms (2.3 in LN years vs. 1.1 EN years). This result is significant at the 85% level using the two-tailed z-score test for the combined regions. El Nino-related interannual variability itself was more severe in the Caribbean Basin region.

4. NPO-related variability

The variability in Atlantic Basin Hurricane activity was further examined with the stratification of the data by ENSO phase and with respect to NPO phase. The results of Gershanov and Barnett (1998) suggest that the SST patterns associated with the NPO act to modulate the strength of the El Nino / La Nina cycle. Thus, it is hypothesized here that interdecadal variations in Atlantic hurricane activity and intensity may be reflected in the data. During NPO2, a mean of 6.2 hurricanes per year was found and this compared to 5.2 events annually which occurred during NPO1. Since the NPO phase 1 displays El Nino-like SST variations in the Pacific (e.g, Minobe, 1997; Gershanov and Barnett, 1998), this result is consistent with the shorter-term ENSO variability. A closer examination shows that there was little difference in weak hurricane occurrence (3.2 in NPO2 vs. 3.4 for NPO1 per year). There were 3.0 intense hurricanes per year in NPO2 vs. 1.8 intense hurricanes during NPO1. These results may explain the drop in intense hurricane activity between 1970 and 1990 (Landsea, 1993). The more frequent occurrence of El Nino events during NPO1 may have reduced the overall hurricane activity, especially in the intense hurricane category.

The NPO2 years (1947 - 1976, 1999) (Table 7) showed limited ENSO-related variability in overall hurricane occurrences. As implied by the results of Gershanov and Barnett (1998), El Nino events are weaker and their effects on mid-latitude circulations downstream are less prevalent. Nonetheless, during El Nino years, there were more weak hurricane events annually than there were intense events (3.7 weak vs. 2.4 intense). During NEU (2.8 weak vs. 3.3 intense) and LN (3.4 weak vs. 2.9 intense) years in contrast, these samples, like the total sample (3.2 weak vs. 2.9 intense), were more evenly divided between the occurrence of weak and intense events.

Key differences, however, were found when examining ENSO-related variability within the NPO1 phase (Table 8). There were more hurricanes during La Nina and Neutral years than during El Nino years (5.6 vs. 3.3 events per year) in NPO1. During Neutral and La Nina years, there was an average of 3.6 weak hurricane events per year, compared to 2.5 events annually during El Nino years. During the La Nina and Neutral (El Nino) years an average of 2.0 (0.8) intense hurricanes occurred annually. The increased intense hurricane activity during La Nina and neutral years is significant at the 90% level. These results, again, explain the decrease in intense hurricane activity found between 1970 and 1990 (e.g., Landsea, 1993, and Landsea et al., 1999). This analysis also shows that the character of ENSO-related variability for hurricane occurrence in the Atlantic Ocean Basin changed within NPO1, since fewer La Nina years were found during this phase. Additionally, the ENSO-related variability in the 62-year sample is likely confined to, and reflects, ENSO related variability in NPO1. This is confirmed by the fact that there was little ENSO-related variability in NPO2 as compared to NPO1. Finally, displaying the data as histograms and testing the distributions for significance (Figs. 4 and 5) demonstrated that each distribution was not significantly different from the expected frequency at the 90% level or greater for NPO1 or NPO2.

The monthly distribution of hurricane activity was stratified by NPO phase as well as ENSO phase (see Table 9). In section 3, it was noted that during La Nina years, the hurricane season tended to start later as hurricane activity did not become more prevalent until July. During both phases of the NPO, the hurricane season became more active in June (July) during El Nino (La Nina) years. In NEU years, July (June) was the month that hurricane activity increased during NPO1 (NPO2); and it decreased in the month of November. The hurricane season winds down during October in El Nino years. In La Nina years, November (October) was the month that hurricane activity decreased for NPO1 (NPO2). Also, the month-by-month interannual variability during NPO1 mirrors that of the total sample in that there was more hurricane activity during La Nina and Neutral years; this was especially evident for the months of August through October. The dearth of hurricane activity during EN years in NPO1 for August to October (September) was significant at the 85% (80%) confidence interval. During NPO2, the results demonstrate no strong ENSO-related variability when examining separate months, or when combining months into "seasons", with the exception of September. In September, there were fewer hurricanes during EN years, but this result was only significant at the 70% confidence level.

An examination of NPO variability in hurricane genesis by sub-ocean basin (Table 10) reveals that the variation in total annual hurricane occurrence in NPO1 (5.2 events) vs. NPO2 (6.2 events) was due to the fact that fewer western Atlantic storms occurred annually during NPO2 years (Table 10). There was remarkably little NPO related variability in the total samples for each sub-basin; however, differences between each basin with respect to ENSO variability were found. For example, in the Caribbean and East Atlantic basins, only one hurricane occurred during all NPO1 El Nino years, while there was dramatically increased activity during LN years. During NPO1 years, there was little interannual variability in the occurrence of Gulf storms. The combination of the Gulf, Caribbean, and East Atlantic Ocean basins together accounted for the increased hurricane activity during NPO1 La Nina years. Within the West Atlantic Ocean basin, there were more storms during El Nino and Neutral years in NPO1. These results suggest that favorable wind shear profiles for hurricane formation shift from the west to the east Atlantic Ocean basins during La Nina years and vice-versa during El Nino years. However, more study is needed to confirm this speculation, along with the cause of this variability.

In the Gulf of Mexico and Caribbean sub-basins, ENSO variability between each phase of the NPO was weakly similar to that of the total sample, i.e., more hurricane activity during La Nina and Neutral years. Within the western and eastern Atlantic, the ENSO-related variability was opposite that of the total sample, i.e., there were more hurricanes in El Nino and Neutral years vs. La Nina years during NPO2. This resulted in the total sample revealing little ENSO-related variability during NPO2.

5. The 1999 Hurricane Season, a Hindcast

This section will address the 1999 hurricane season, which was winding down at the time of this writing. The CSU/TPC seasonal forecast called for an active hurricane season in June and August due partly to prevailing La Nina conditions (14 named storms and 9 hurricanes). Their forecasts are self-evaluated, and they have shown that their forecasts are improving with some skill. It is not the intent here to evaluate the CSU/TPC forecast; however, the 1999 hurricane season will be put into the context of the results found here. It is likely that, using the criterion outlined on the COAPS website, that 1999 will be labeled a La Nina year. Also, Kerr (1999) reports that during the latter half of 1998, the NPO phase had switched to NPO2 (see Table 1).

There were eight hurricanes reported in 1999. During August, September, October, and November there were three storms (Bret - Cat. 4, Cindy - Cat. 4, and Dennis - Cat. 2), two storms (Floyd - Cat. 4, Gert - Cat 4), two storms (Irene - Cat. 2, and Jose - Cat. 2), and one storm (Lenny - Cat. 4), respectively. This season was unusual in that a total of five category 4 storms were noted (most ever since reliable records began in the mid-1940's), even though this season did not witness the most ever intense (combined category 3,4, and 5) hurricanes. This season also featured a very destructive US landfalling storm (Floyd), and the latest observed category 4 storm (since reliable records began), Lenny. Lenny was an incredible mid-November Caribbean storm (150 mph winds and 929 hPa minimum pressure) that affected the Lesser Antilles by moving from west to east instead of east to west.

Obviously, there are season-to-season variations, which make up the average, so a formal “skill”-type score or analysis is not attempted here. Using the results of this study (*round numbers will be taken from the results*), we would expect six hurricanes (6). Also, especially more intense hurricanes (3 weak and 3 intense hurricanes) should occur during NPO2 La Nina years. The expected climatological frequency (climatology) for hurricane occurrence would suggest that more weak storms would occur versus strong storms. During the 1999 season, there were 8 hurricanes (3 weak and 5 intense storms); thus, the results of this study would be a useful tool in this sense (outperforming climatology). Breaking down the results by individual categories, we would expect two (two), two (one), one (one), and one (one) category 1,2,3, and 4 storms, respectively, in a La Nina NPO2 (climatological) year. This categorization, being the most detailed evaluation used here, would be the least useful parameter. During the 1999 season there were three category 2 storms and five category 4 storms.

Examining the 1999 season by month reveals a potentially contracted hurricane season, which is slow to evolve (July or August) and ends earlier (October) in the period. We should expect two (one) storms in August, three (two) in September, and one (one) in October given the results found here, for a La Nina NPO2 (climatological) year. During the 1999 season, there were three August storms, two September storms, and two October storms observed in the Atlantic Ocean basin. In addition, there was also one November storm. The progression of the

1999 season was more similar to the La Nina NPO2 result than to climatology in the number and distribution of storms, except for the one November storm (compare Table 5 and Table 9).

An examination by sub-basin reveals that one storm each should originate in the Caribbean, Gulf, and East Atlantic basins, and three storms originating within the Western Atlantic during La Nina NPO2 and climatological years. During the 1999 season, one storm originated in the Gulf and two each in the Caribbean and Eastern Atlantic basins, while three storms occurred in the Western Atlantic Ocean basin, respectively. Thus, in general terms, the results of this study passed the test when a "hindcast" derived from these data were compared to the observed 1999 Atlantic Ocean basin hurricane activity. The results also show that the observations matched the La Nina NPO2 results better than the undifferentiated climatological expectations in this informal analysis.

6. Summary and Conclusions

An analysis of hurricane occurrence within the Atlantic Ocean Basin has revealed several key results. The 62-year data set was examined to find short and long-term trends and interannual variability. The climatology shows not only a peak in hurricane occurrence for all categories during the month of September, but that more hurricane events occurred within the second half of the nominal hurricane season. Although there has been a slight increase in global surface temperatures, there has been relatively little trend in the overall occurrence of hurricanes within the Atlantic Ocean Basin, a result that agrees with the findings of Landsea (1993). This weak trend reflects an upward trend in category 1 hurricanes, which is countered by downward or weak trends in the occurrence of category 2-5 hurricanes.

When examining ENSO-related variability in hurricane occurrence it was found that there are fewer hurricanes during El Nino years as opposed to La Nina years; however, this result is not statistically significant at the 95% or 99% levels. It should be noted here that many of the key results presented here were significant at the 70% - 90% confidence level indicating a 'likely' relationship. An analysis by category reveals that there were fewer intense hurricane events during El Nino years than La Nina years, and this result is significant at 85%. Thus, the decrease in intense hurricane occurrences from 1970 to 1990 may have then been related to the increase in the number of El Nino events over those two decades. A monthly analysis of hurricane activity revealed that the month-by-month variability is similar to that of the total variability for every month except June. La Nina years were also shown to become more active later in the year. Stratifying hurricane occurrence by genesis region indicated that there were fewer Caribbean and Gulf storms during El Nino years, while the number of hurricanes forming in the Atlantic sub-basin were similar for each phase of ENSO.

When examining interannual variability with respect to the NPO, it was shown that there is little difference in the distribution across each category of hurricane occurrence over each phase of the NPO (Table 7 and 8). The key differences, however, emerge when a comparison of each phase is made after stratifying the data by ENSO phase. There was relatively little ENSO-related variability found within the NPO2 phase, with the exception that there were more intense hurricane events during the neutral phase during NPO2. During NPO1, however, there was significant ENSO-related variability. Only 3.3 hurricanes per year were observed in El Nino years while there were 5.6 hurricane events per year during the La Nina and Neutral years. Examining the results by month revealed that La Nina year hurricane activity tended to be skewed toward the latter part of hurricane season (NPO1), or encompassed a shorter season than

(NPO2) El Nino or Neutral hurricane seasons. Stratifying by hurricane genesis region indicated that the tendency for more hurricanes to form in La Nina years during NPO1 was strongly influenced by storms being generated in the Caribbean and Eastern Atlantic. Only two storms formed in these regions during El Nino years. During NPO2 there was a weak tendency for more (fewer) storms forming in the Gulf and Caribbean (West and East Atlantic) sub-regions during La Nina years, while the reverse occurred for El Nino years. This study demonstrated that ENSO-related variability that is found in the 62-year sample is primarily confined to NPO1 years.

The results of this study suggest that during the next few years hurricane activity within the Atlantic Ocean basin may increase and demonstrate less ENSO-related variability than that in recent years. Alternatively, hurricane activity may again become similar to that of the 1940s, 1950s, and 1960s. These years witnessed many damaging landfalling hurricanes in the United States. However, the trends in hurricane activity are related to many other factors as well, thus, these results presented here must be looked at only within the context of this study. Finally, a brief examination of the 1999 hurricane season shows that the results obtained here provided a reasonable “hindcast” for the season’s hurricane activity in general terms.

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8. References

Aller, D., 1999: Tropical cyclones in 1997. *Weather*, **54**, 152 - 153.

Bove, M.C., J.B. Elsner, C.W. Landsea, N. Xufeng, and J.J. O'Brien, 1998: Effect of El Nino on U.S. landfalling hurricanes. *Bull. Amer. Meteor. Soc*., **79**, 2477 - 2482.

Colorado State Press Release, 1999: Colorado State University. [Available on line at http://tropical.atmos.colostate.edu/forecasts]

Gershanov, A., and T.P. Barnett, 1998: Inderdecadal modulation of ENSO teleconnections. *Bull. Amer. Meteor. Soc*., **79**, 2715 - 2725.

Goldenberg, S.B., and L.J. Shapiro, 1996: Physical mechanisms for the association of El Nino and West African rainfall with Atlantic major hurricane activity. *J. Climate*, **9,** 1169 - 1187.

Gray, W.M., 1984a: Atlantic season hurricane frequency. Part 1: El Nino and 30 mb Quasi Biennial Oscillation influences. *Mon. Wea. Rev.*, **112**, 1649 - 1668.

Gray, W.M., 1984b: Atlantic season hurricane frequency. Part 2: Forecasting its variability. *Mon. Wea. Rev.*, **112**, 1669 - 1683.

Gray, W.M., 1998: Hypothesis on the cause of global multidecadal climate change. *Preprints of the Ninth Symposium on Global Change Studies*, 271 - 275.

Gray, W.M., C.W. Landsea, P.W. Mielke, Jr., and K.J. Berry, 1993: Prediciting Atlantic Basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting*, **8**, 73 - 86.

Gray, W.M., J.D. Sheaffer, and C.W. Landsea, 1997: Climate trends associated with multidecadal variability of Atlantic hurricane activity. *Hurricanes, Climate, and Socioeconomic Impacts*, 15 - 53. Springer, Berlin, H.F. Diaz and R.S. Pulwarty, Eds.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gry, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster, K. McGuffie, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Amer. Meteor. Soc.*, **79**, 19 - 38.

Houghton, J.T., L.G. Meira-Filho, B.A. Callander, N. Harris, A. Kattenberg, and K Maskell, 1996: *Climate Change 1995: The science of climate change, contributions of working group I to the Intergovernmental Panel on Climate Change*, Cambridge University Press, 572 pp.

Hurrell, J.W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science*, **269**, 676 - 679.

Hurrell, J.W., 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperatures. *Geophys. Res. Let.*, **23**, 665 - 668.

Jarvinen, B.R., C.J. Neumann, and M.A.S. Davis, 1984: A tropical cyclone data tape for the North Atlantic Basin, 1886 - 1983: Contents, limitations, and uses. *NOAA Tech. Memo. NWS NHC 22*, Coral Gables, Florida, 21pp.

Kerr, R.A., 1999: Big El Ninos ride the back of slower climate change. *Science*, **283**, 1108-1109.

Landsea, C.W., 1993: A climatology of intense (or Major) Atlantic hurricanes. *Mon. Wea. Rev.*, **121**, 1703 - 1713.

Landsea, C.W., R.A. Pielke Jr., A. Mestas-Nuez, and J. Knaff, 1999: Atlantic Basin hurricanes: Indicies of climate changes. *Climatic Change,* **42***,* 89 - 129.

Landsea, C.W., and W.M. Gray, 1992: The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, **5**, 435 - 453.

McPhaden, M.J., 1999: Climate oscillations: Genesis and evolution of the 1997 - 1998 El Nino. *Science*, **283**, 950 - 954.

Minobe, S., 1997: A 50 - 70 year climatic oscillation over the North Pacific and North America. *Geophys. Res. Lett.*, **24**, 683 - 686.

Neter, J., W. Wasserman, and G.A. Whitmore, 1988: *Applied Statistics, 3rd edition*. Boston: Allyn and Bacon, 1006 pp.

O'Brien, J.J., T.S. Richards, and A.C. Davis, 1996: The effect of El Nino on U.S. landfalling hurricanes. *Bull. Amer. Meteor. Soc.*, **77**, 773 - 774.

Pielke, R.A., and C.N. Landsea, 1999: La Nina, El Nino, and Atlantic hurricane damages in the United States. *Bull. Amer. Meteor. Soc.*, **80**, 2027 - 2033.

Rappaport, E.N., 1999: Atlantic hurricane season of 1997. *Mon. Wea. Rev.*, **127**, 2012 - 2026.

Shapiro, L.J., 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Wea. Rev.*, **115**, 1598 - 1614.

Simpson, R.H., 1974: The hurricane disaster potential scale. *Weatherwise*, **27**, 169 and 186.

Singer, F., 1997: Hot talk, cold science. Global warming's unfinished debate. The Independent Institute, Oakland, CA, 110 pp.

Wallace, J.M., and D.S. Gutzler, 1981: Teleconnections in the Northern Hemisphere winter. *Mon. Wea. Rev*., **109**, 784 - 812.

Footnotes

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://masig.fsu.edu.

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

La Nina (LN)	Neutral (NEU)	El Nino (EN)
1938	1939	1940
1942	1941	1951
1944	1943	1957
1949	1945-1948	1963
1954	1950	1965
1955	1952	1969
1956	1953	1972
1964	1958-1962	1976
1967	1966	1982
1970	1968	1986
1971	1974	1987
1973	1977-1981	1991
1975	1983	1997
1988	1984	
1998	1985	
1999	1989	
	1990	
	1992-1996	

Table 2. Phases of the North Pacific Oscillation (NPO) since 1933.

NPO 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 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.

category	1940-69	1970-89	1990-99	All
Cat. 1,2	2.9	3.4	3.8	3.3
Cat. 3-5	2.9	1.6	2.6	2.4
Cat. 4,5	1.4	0.9	1.4	1.2
Total	5.8	5.0	6.4	5.7

Table 4. The average annual occurrence of Atlantic Ocean Basin hurricanes versus El Nino / La Nina phase for each category.

	All	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
LN	6.2	1.9	1.6	1.1	1.1	0.5
NEU	5.8	2.3	0.9	1.3	0.9	0.4
EN	4.8	2.1	1.0	1.0	0.4	0.3
Total	5.7	2.2	1.1	1.2	0.8	0.4

Table 5. The mean annual occurrence of hurricanes stratified by ENSO phase and month.

	May	June	July	August	Septmbr	Octbr	Novmbr	Decmbr
LN	0.06	0.06	0.25	1.56	2.69	1.19	0.19	0.06
NEU	0	0.27	0.36	1.27	2.39	1.24	0.36	0.03
EN	0.08	0.31	0.15	1.31	1.38	1.07	0.15	0
TOT	0.03	0.23	0.29	1.35	2.26	1.19	0.27	0.03

Table 6. The average annual occurrence of hurricanes 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	6.2	1.2	1.1	2.7	1.2
NEU	5.8	0.9	0.9	2.9	1.1
EN	4.8	0.4	0.7	2.9	0.9
Total	5.7	0.9	0.9	2.9	1.1

Table 7. The average annual occurrence of Atlantic hurricanes stratified by ENSO phase and category during NPO2 (1947 - 1976, 1999).

	All	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
LN	6.2	1.9	1.5	1.3	1.2	0.4
NEU	6.1	2.0	0.8	1.8	1.0	0.5
EN	6.1	2.3	1.4	1.4	0.4	0.6
Total	6.1	2.0	1.2	1.5	0.9	0.5

Table 8. The average annual occurrence of Atlantic hurricanes stratified by ENSO phase and category during NPO1 (1938-46, 1977-98).

	All	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
LN	5.6	1.8	1.8	0.8	0.8	0.4
NEU	5.6	2.5	1.1	0.9	0.8	0.3
EN	3.3	2.0	0.5	0.5	0.3	0.0
Total	5.2	2.3	1.1	0.8	0.7	0.3

Table 9. The mean annual occurrence of hurricanes stratified by ENSO phase and month for a) NPO1, and b) NPO2.

a) NPO1

	May	June	July	August	Septmbr	Octbr	Novmbr	Decmbr
LN	0	0	0.20	1.80	2.60	0.80	0.40	0
NEU	0	0.10	0.60	1.35	2.20	1.05	0.45	0.05
EN	0	0.33	0.33	0.83	1.17	0.50	0.16	0
TOT	0	0.13	0.35	1.32	2.06	0.90	0.39	0.03

b) NPO2

	May	June	July	August	Septmbr	Octbr	Novmbr	Decmbr
LN	0.09	0.09	0.27	1.45	2.73	1.36	0.09	0.09
NEU	0	0.54	0.31	1.15	2.69	1.54	0.23	0
EN	0.14	0.29	0	1.71	1.57	1.57	0.14	0
TOT	0.06	0.32	0.23	1.39	2.45	1.48	0.16	0.03

Table 10. The average annual occurrence of hurricanes for each sub-ocean basin as stratified by NPO and ENSO phase (NPO1/NPO2).

	All	Crrb.	Gulf	W Atl	E Atl
LN	5.6/6.2	1.8/0.9	0.8/1.3	1.6/3.2	1.6/0.9
NEU	5.6/6.1	0.7/1.2	1.1/0.7	2.7/3.2	1.1/1.1
EN	3.3/6.1	0.2/0.6	0.8/0.6	2.2/3.5	0.2/1.4
Total	5.2/6.1	0.8/0.9	1.0/0.9	2.4/3.3	1.0/1.1

Figure 1. A map of the Atlantic Ocean basin. The Gulf of Mexico, Caribbean, West Atlantic, and East Atlantic sub-basins are labeled and denoted with heavy line.

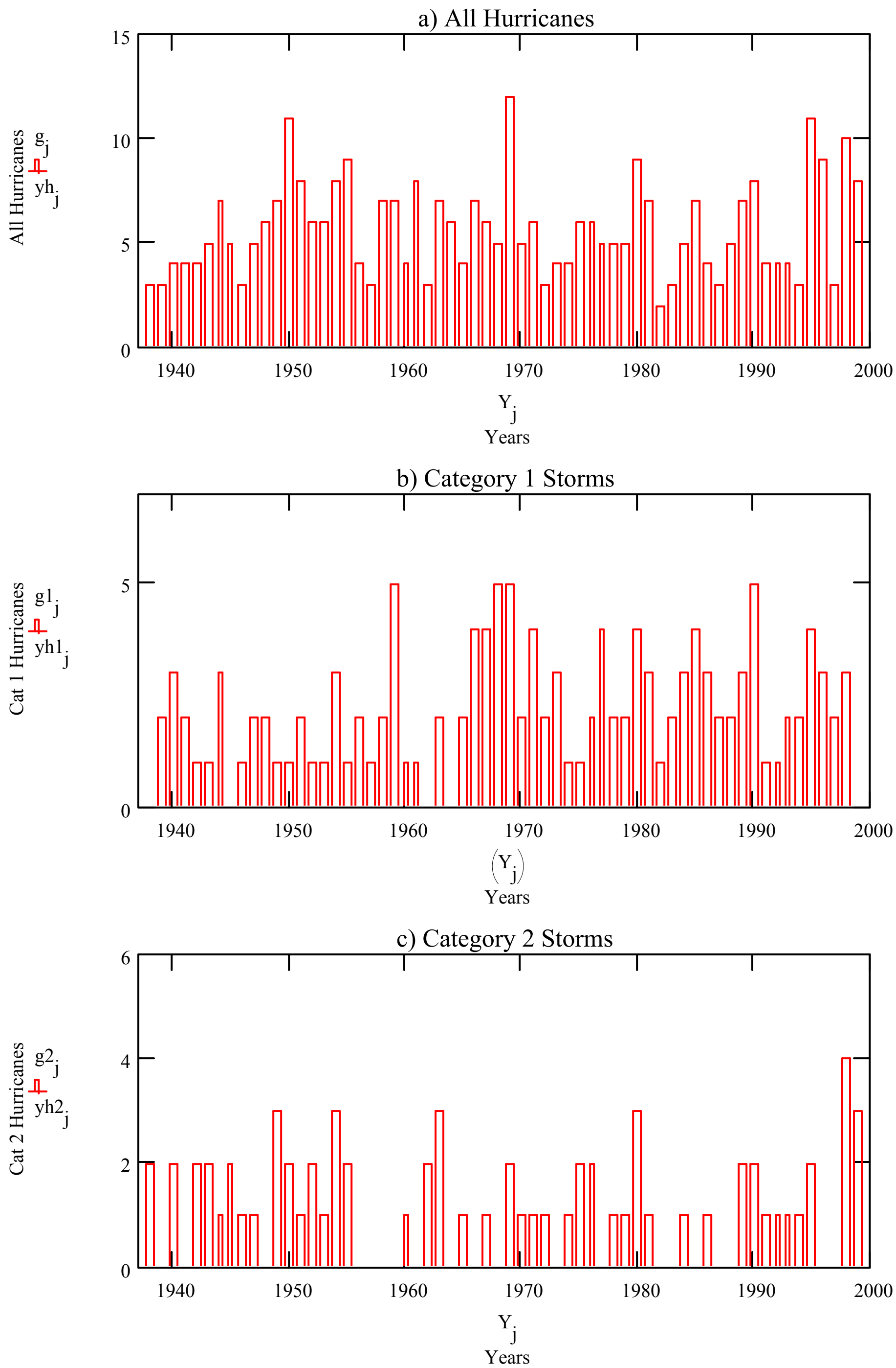

Figure 2. Bar graphs of number of Atlantic Ocean Basin hurricanes versus year for a) the total sample, b) category 1, c) category 2, d) category 3, e) category 4, and f) category 5 hurricanes.

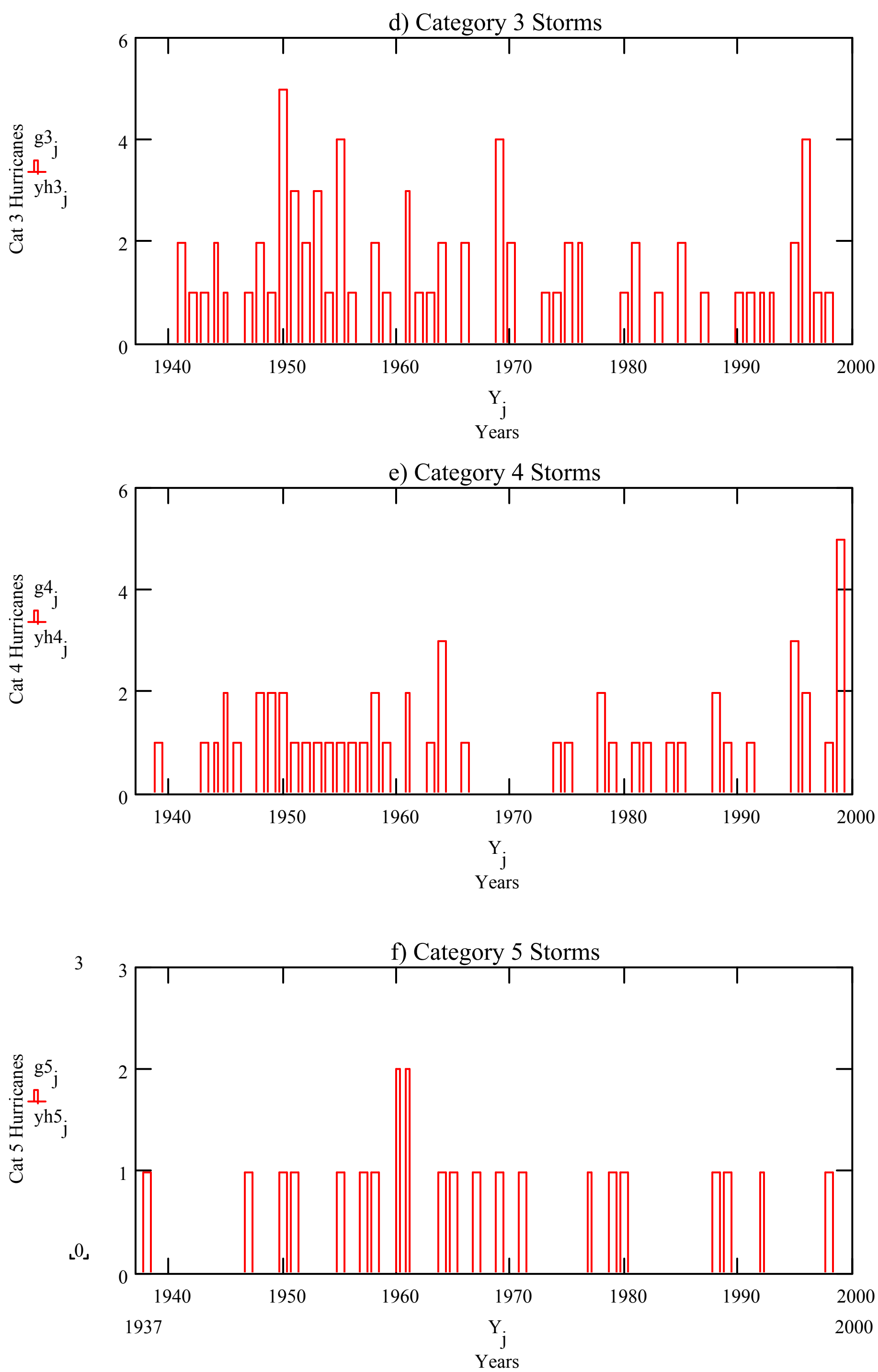

Figure 2. Continued

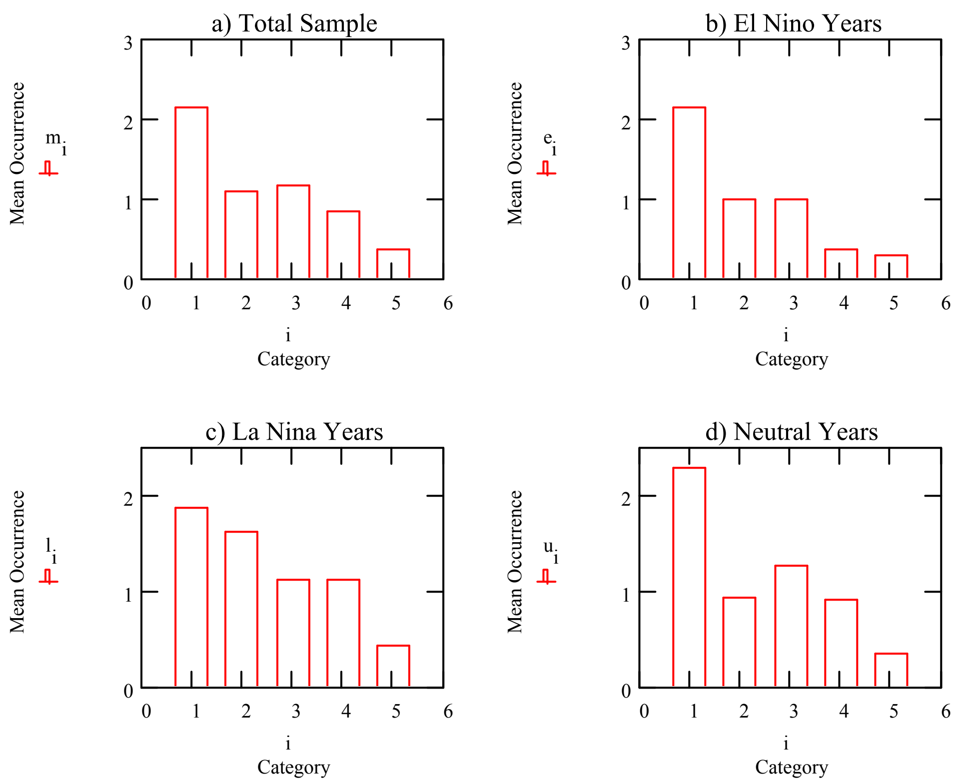

Figure 3. Histograms of average annual hurricane frequency separated by category for a) the total sample, b) El Nino years, c) La Nina years, and d) Neutral years.

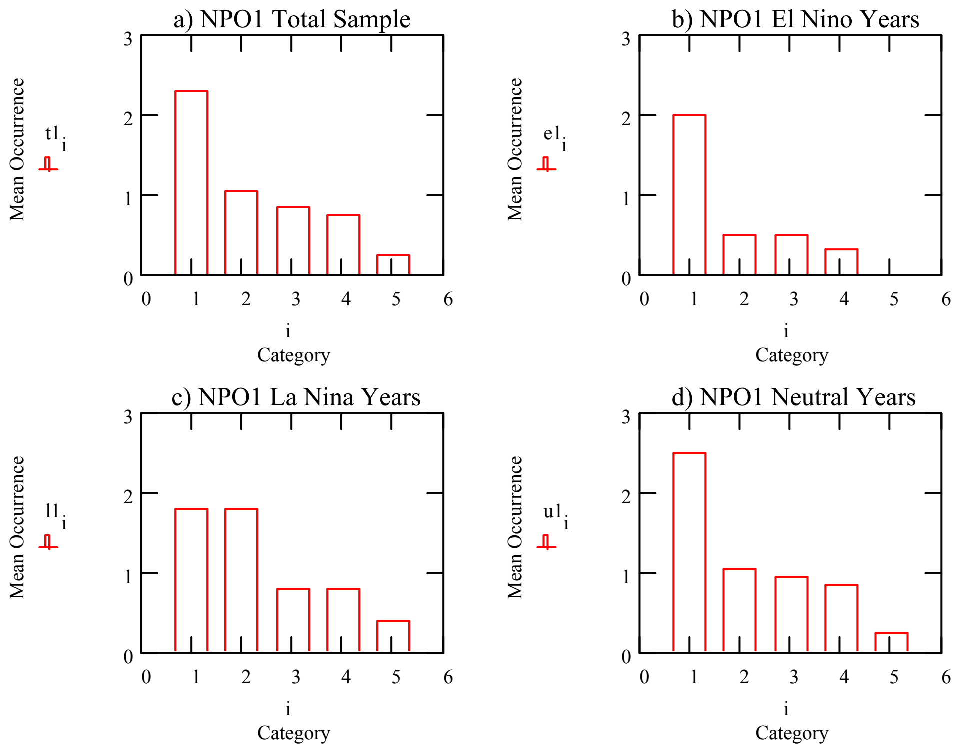

Figure 4. As in Fig. 3 except for NPO1 years (1938 - 1946, 1977 - 1998).

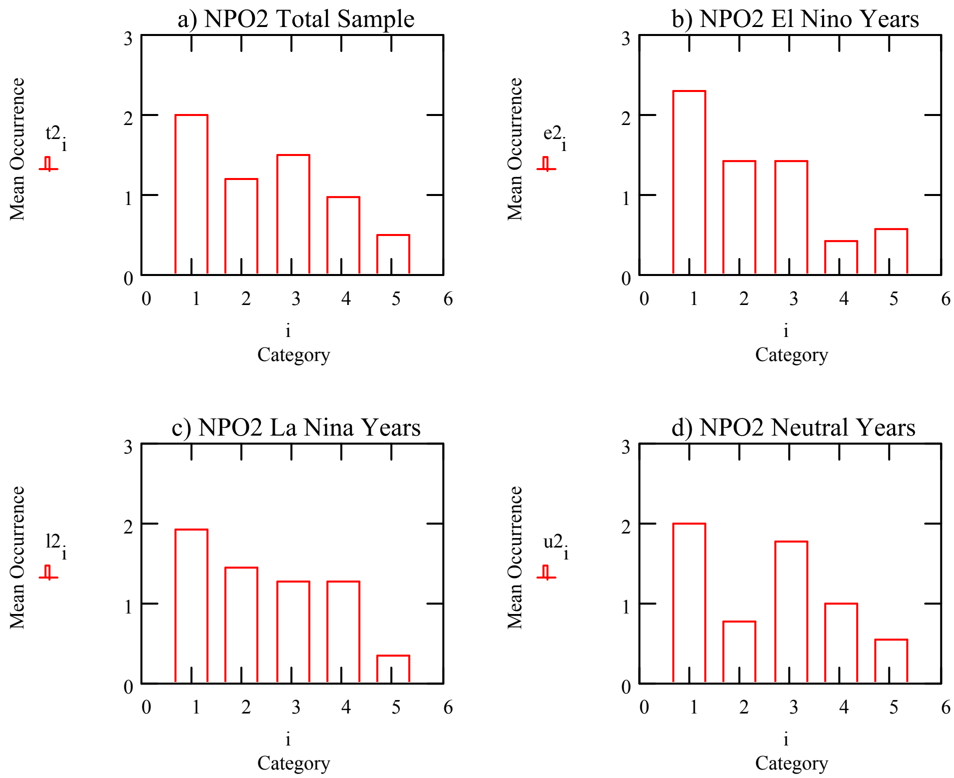

Figure 5. As in Fig. 3 except for NPO2 years (1947 - 1976, 1999).