3A.4 CARIBBEAN/CENTRAL AMERICAN HURRICANE LANDFALL PROBABILITIES

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1. INTRODUCTION

The Tropical Meteorology Project (TMP) at Colorado State University has been issuing Atlantic basin seasonal hurricane forecasts since 1984 (Gray 1984b). The TMP began issuing landfall probabilities for the United States coastline with their August 1998 prediction (Gray et al. 1998). More recently, the TMP began developing probabilities of Caribbean/Central American landfall, which are discussed in detail in Klotzbach (2010, manuscript submitted to *J.* Climate). The Caribbean shows greater year-to-year variability with large-scale phenomena such as El Niño – Southern Oscillation (ENSO) (Rasmusson and Carpenter 1982, Tartaglione et al. 2003) and the Atlantic Multi-Decadal Oscillation (AMO) (Gray et al. 1997, Goldenberg et al. 2001) then does the rest of the tropical Atlantic. This paper discusses how landfall probabilities were calculated for the Caribbean and Central America and then demonstrates the strong relationships that are present between ENSO, the AMO, and Caribbean basin tropical cyclones.

2. DATA

Caribbean basin hurricane activity was calculated from the National Hurricane Center's Atlantic Tracks file database (Jarvinen et al. 1984). The GIS version of the Atlantic Tracks file is available for download from http://csc-s-maps-q.csc.noaa.gov/hurricanes/download.jsp. Climatological calculations for Caribbean/Central American landfall are based on the period from 1900-2008, including the reanalyzed data from 1900-1920 as part of the Atlantic Hurricane Database Re-Analysis Project (Landsea et al., 2004, 2008).

The Hadley SST temperature dataset HadISST1 (Rayner et al. 2003) was used for defining ENSO events. The Nino 3.4 index (5°S-5°N, 120°-170°W) as averaged over the August-October period was the index used to determine which years were classified as El Niño, La Niña or neutral. The older HadISST1 dataset was used for ENSO, given the fact that it includes interpolation for missing data. Some data during the earlier period of the 20th century was missing in the tropical Pacific.

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The HadSST2 dataset (Rayner et al. 2006) was used to define AMO events. The AMO was evaluated from 50°-60°N, 10-50°W, in a similar manner to what was done in Klotzbach and Gray (2008).

3. CLIMATOLOGICAL CARIBBEAN AND CENTRAL AMERICAN LANDFALL PROBABILITIES

Climatological probabilities of landfall were calculated using the ArcMap software available from the Environmental Systems Research Institute (ESRI). All tropical cyclones that were within 50 and 100 miles of each island or landmass over the period from 1900-2008 were selected. The maximum intensity that each tropical cyclone reached when within 50 or 100 miles of the island was set as its "landfall" intensity.

In order to translate the number of tropical cyclones impacting an island into an annual probability, the Poisson distribution was used, due to the fact that the Poisson distribution limits outcomes to non-negative integers (Elsner and Schmertmann 1993). The Poisson distribution is defined by the following formula:

$$EP = p^{-x}/e^{p}x! \quad (1)$$

where EP is the expected probability, p is the annual average number of tropical cyclones that have occurred in the past 109 years and x is any particular number of storms expected in the upcoming year. Table 1 displays the climatological probability of one or more tropical cyclones tracking within 50 miles for several islands in the Caribbean and countries in Central America.

Table 1: Probabilities of one or more named storms (NS), hurricanes (H) and major hurricanes (MH) tracking within 50 miles of several islands in the Caribbean and countries in Central America.

Country	Prob. NS (50 Miles)	Prob. H (50 Miles)	Prob. MH (50 Miles)
Bahamas, The	72%	45%	25%
Belize	35%	18%	8%
Cuba	71%	46%	25%
Guadeloupe	29%	16%	6%
Guatemala	29%	10%	3%
Haiti	41%	21%	9%
Jamaica	40%	20%	10%
Nicaragua	27%	12%	7%
Puerto Rico	32%	14%	4%
Turks and Caicos	31%	14%	8%

Probabilities for any one particular island or landmass being impacted in a particular year are quite small. However, these probabilities grow considerably when multiple-year periods are considered. Table 2 displays probabilities of a major hurricane being within 50 miles of various islands of the Caribbean and countries in Central America for 5, 10, and 50-year periods, utilizing the binomial distribution function to make the calculations. Probabilities are generally over 90% for most islands and countries when the 50-year period is considered, thereby illustrating the imperative nature of building hurricane-resistant structures in these areas.

$$\text{Multi-Year Probability} = 1 - (1 - \text{One-Year Prob.})^{\text{Number of Years}} \quad (2)$$

Table 2: Probability of a major hurricane tracking within 50 miles of selected islands in the Caribbean and countries in Central America over 5, 10 and 50-year periods.

Country	Prob. MH (50 Miles) 5 Years	Prob. MH (50 Miles) 10 Years	Prob. MH (50 Miles) 50 Years
Bahamas, The	78%	95%	>99%
Belize	36%	59%	99%
Cuba	79%	96%	>99%
Guadeloupe	29%	50%	97%
Guatemala	14%	26%	77%
Haiti	39%	63%	99%
Jamaica	42%	66%	>99%
Nicaragua	33%	55%	98%
Puerto Rico	22%	39%	92%
Turks and Caicos	36%	59%	99%

4. IMPACTS OF ENSO ON CARIBBEAN LANDFALL FREQUENCY

Several studies have documented the strong relationship between ENSO and overall Atlantic basin hurricane activity (e.g., Gray 1984a). This paper focuses on the dramatic alterations that exist for Caribbean activity, defined as tropical cyclone activity occurring in a box from 10-20°N, 60-88°W. Tartaglione et al. (2003) demonstrated significant variability in the northern portion of the Caribbean basin given particular phases of ENSO, and this study investigates this variability in more detail. Annual statistics of Caribbean hurricane activity from 1900-2008 were first tabulated from the Atlantic Tracks file database. Hurricane activity in the Caribbean varies considerably from year-to-year, from a maximum of 15 named storms in 1933 to eight years with no named storm activity in the Caribbean basin.

ENSO's impacts in the Caribbean were evaluated through examination of August-October values of the Nino 3.4 index. The 25 warmest August-October periods were defined as El Niño years (SST threshold of 0.56°C), the 25 coldest August-October periods were defined as La Niña years (SST threshold of -0.50°C), while all remaining 58 years were classified as neutral. Table 3 displays the per-year average number of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), major hurricanes (MH), major hurricane days (MHD) and Accumulated Cyclone Energy (ACE) for the 10 warmest, the 25 warmest, neutral, the 25 coldest and the 10 coldest August-October periods. Ratios are also provided. All differences between 25 coldest and 25 warmest means are statistically significant at the 95% level using a one-tailed Student's t-test. In general the ratios between the 10 coldest and 10 warmest years are even larger, and all differences in means are statistically significant at the 95% level except for major hurricanes. Figure 1 displays the tracks of major hurricanes for the 10 coldest versus 10 warmest years, illustrating the dramatic impact that ENSO has on Caribbean hurricanes.

Table 3: The average per-year number of NS, NSD, H, HD, MH, MHD and ACE for the 10 coldest, 25 coldest, neutral, 25 warmest and 10 warmest August-October periods in the Nino 3.4 region. The 25 coldest/25 warmest ratio and 10 coldest/10 warmest ratio are also provided.

	NS	NSD	H	HD	MH	MHD	ACE
10 Coldest	4.3	12.5	2.5	6.0	1.0	2.2	27.4
25 Coldest	4.6	11.4	2.3	4.7	0.9	1.5	21.8
Neutral	3.2	1.4	0.7	7.3	2.8	1.0	13.3
25 Warmest	1.6	3.3	0.7	1.4	0.4	0.6	6.9
10 Warmest	1.2	2.6	0.5	0.9	0.3	0.3	4.3
25 Coldest/ 25 Warmest	2.9	3.4	3.2	3.4	2.4	2.4	3.1
10 Coldest/ 10 Warmest	3.6	4.8	5.0	6.7	3.3	7.3	6.3

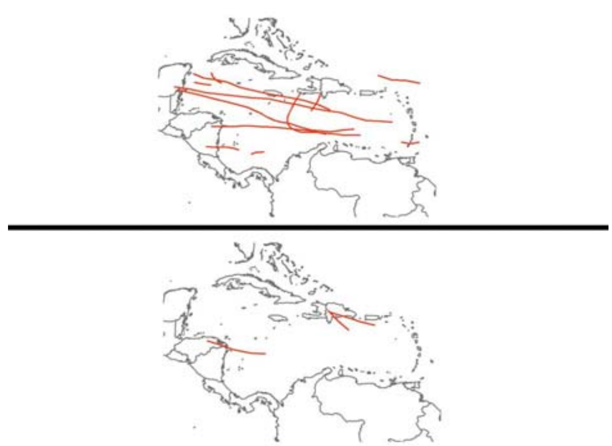

Figure 1: Tracks of major hurricanes in the 10 warmest and 10 coldest ENSO years. There were 22.25 major hurricane days in the 10 coldest ENSO years compared with only 3 major hurricane days in the 10 warmest ENSO years.

Figure 2 displays the probabilities of one or more named storms, hurricanes and major hurricanes tracking through the Caribbean given various ENSO categories. Annual averages were translated into probabilities using the Poisson distribution. As the magnitude of a warm ENSO event increases, the probability of hurricane and major hurricane activity in the Caribbean drops markedly. For example, the probability of a major hurricane drops from 63% in the ten coldest La Niñas to 26% in the ten warmest El Niño s.

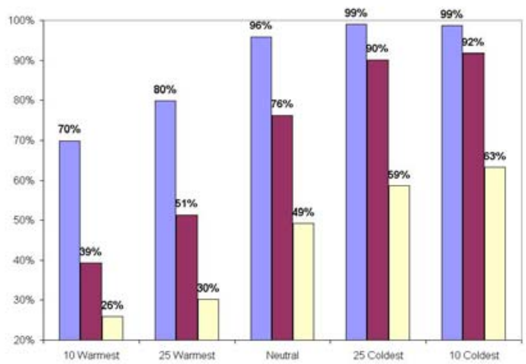

Figure 2: Probabilities of landfall for named storms (purple columns), hurricanes (red columns) and major hurricanes (yellow columns) for various ENSO conditions.

In general, El Niño events are thought to reduce Atlantic hurricane activity due to alterations in levels of vertical wind shear (e.g., Gray 1984a). This is found to be the case in the Caribbean as well. The difference in August-October-averaged 200-850 mb vertical wind shear in the Caribbean is approximately 4 ms^{-1} between the 10 warmest and 10 coldest ENSO events over the period from 1948-2009 using the NCEP/NCAR Reanalysis data (Kistler et al. 2001).

5. IMPACTS OF THE AMO ON CARIBBEAN LANDFALL FREQUENCY

The AMO has been documented to impact Atlantic basin hurricane frequency through alterations in tropical Atlantic sea surface temperatures, alterations in vertical wind shear and alterations in the position of the Inter-tropical Convergence Zone (Gray et al. 1997, Goldenberg et al. 2001, Vimont and Kossin 2007, Klotzbach and Gray 2008).

Extending the definition of positive and negative AMO periods classified in Klotzbach and Gray (2008), the periods between 1900-1925 and 1970-1994 are defined as cold AMO periods, while the periods from 1926-1969 and 1995-2008 are defined as warm AMO periods. Table 4 displays the average per-year tropical cyclone activity for the four AMO periods. The ratios are much stronger for the more recent 1995-2008 versus the 1970-1994 period, when compared with the earlier time period. These findings are similar to the findings for the entire Atlantic basin found in Klotzbach and Gray (2008). None of the differences in means between 1900-1925 and 1926-1969 are statistically significant, while all differences in means between 1970-1994 and 1995-2008 are significant at the 95% level.

Table 4: The average per-year number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days and ACE that occurred during the periods from 1900-1925, 1926-1969, 1970-1994 and 1995-2008, respectively. Ratios between the 1926-1969 and 1900-1925 time period and between 1995-2008 and 1970-1994 are provided.

	NS	NSD	H	HD	MH	MHD	ACE
1900-1925 (AMO Cold)	3.0	1.3	0.5	7.6	2.8	0.6	11.8
1926-1969 (AMO Warm)	3.6	1.7	0.7	8.2	3.3	1.1	14.8
1970-1994 (AMO Cold)	2.0	0.8	0.4	4.0	1.3	0.7	7.7
1995-2008 (AMO Warm)	4.3	2.5	1.4	10.2	4.7	2.3	24.8
1926-1969/ 1900-1925	1.2	1.3	1.5	1.1	1.2	1.9	1.3
1995-2008/ 1970-1994	2.1	3.3	3.8	2.6	3.5	3.4	3.2

6. COMBINED IMPACTS OF ENSO AND THE AMO ON CARIBBEAN LANDFALL FREQUENCY

The combination of ENSO and the AMO plays a very strong role in modulating Caribbean landfall frequency. Table 5 displays the per-year average for the top 10 warm ENSO events when the AMO was negative and the top 10 cold ENSO events when the AMO was positive. Very strong differences are seen between these two conditions, with all differences in means being statistically significant at the 99% level. These differences are also considerable when converted into annual probabilities. For example, the probability of one or more hurricanes impacting the Caribbean when the AMO is positive in one of the 10 strongest cold ENSO events is in progress is 95%, compared with only 18% when a warm ENSO event is in progress and the AMO is negative.

Table 5: The average per-year number of named storms, named storm days, hurricanes, hurricane days, major hurricanes, major hurricane days and ACE that occurred during the 10 coldest ENSO events when the AMO was positive and the 10 warmest ENSO events when the AMO was negative. The ratio between these two sets of climate conditions is also provided.

	NS	NSD	H	HD	MH	MHD	ACE
ENSO- AMO+	5.6	14.7	2.9	6.5	1.4	2.8	32.0
ENSO+ AMO-	1.4	2.2	0.2	0.2	0.1	0.1	1.9
ENSO- AMO+/ ENSO+ AMO-	4.0	6.7	14.5	37.1	14.0	56.0	16.7

Figure 3 displays Caribbean basin hurricanes for the 10 coldest ENSO years in a warm AMO phase, compared with Caribbean basin hurricanes for the 10 warmest ENSO years in a cold AMO phase. Sixty-five hurricane days occurred in the cold ENSO years and warm AMO conditions, compared with only 1.75 hurricane days in the warm ENSO years and cold AMO conditions. Therefore, a combination of knowing which AMO phase is occurring for a particular season combined with a good ENSO forecast provides considerable information regarding the likelihood of Caribbean hurricane activity.

Figure 3: Tracks of hurricanes (65 hurricane days) in the ten coldest ENSO events when the AMO was positive compared with tracks of hurricanes (1.75 hurricane days) in the ten warmest ENSO years when the AMO was negative.

7. CONCLUSIONS AND FUTURE WORK

Climatological probabilities of landfall for every island in the Caribbean and every country in Central America were calculated using historical hurricane data from the period between 1900-2008. Significant relationships were demonstrated between Caribbean activity and phase of ENSO. Less significant relationships were seen between the AMO and Caribbean activity; however, in combination, the AMO and ENSO provide very powerful signals regarding levels of Caribbean hurricane activity.

In the future, I intend to investigate development of a seasonal forecast for Caribbean hurricane activity, using the AMO, ENSO and various other large-scale climate parameters.

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