QUALITATIVE DISCUSSION OF ATLANTIC BASIN SEASONAL HURRICANE ACTIVITY FOR 2013

We discontinued our early December quantitative hurricane forecast last year and are now giving a more qualitative discussion of the factors which will determine next year's Atlantic basin hurricane activity. One of the big uncertainties for the 2013 Atlantic basin hurricane season is whether or not El Niño will develop.

Our first quantitative forecast for 2013 will be issued on Wednesday, April 10.

(as of 7 December 2012)

By Philip J. Klotzbach[1] and William M. Gray[2]

This discussion as well as past forecasts and verifications are available online at
http://hurricane.atmos.colostate.edu

Emily Wilmsen, Colorado State University Media Representative, (970-491-6432) is available to answer various questions about this discussion

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ABSTRACT

We are providing a qualitative discussion of features likely to impact the 2013 Atlantic basin hurricane season rather than a specific numbers forecast. This outlook for 2013 will give our assessment of the probability of four potential scenarios for Net Tropical Cyclone (NTC) activity.

We have developed a new way of assessing next year's activity in terms of two primary physical parameters:

1. the strength of the Atlantic thermohaline circulation (THC)
2. the phase of ENSO

We have been in an active era for Atlantic basin tropical cyclones since 1995, and we expect that typical conditions associated with a positive Atlantic Multi-Decadal Oscillation (AMO) and strong thermohaline circulation (THC) will continue. One of the big challenges for 2013 is whether or not El Niño will develop for the 2013 hurricane season. Since El Niño never fully developed in 2012, and we have since returned to neutral conditions, there is the possibility that an El Niño event will develop next year. Given the persistent negative North Atlantic Oscillation (NAO) and positive thermohaline circulation (THC) conditions that have prevailed over the past several months, we expect to see tropical Atlantic sea surface temperatures (SSTs) next spring at warmer levels than were experienced in the spring of 2012. We anticipate that the 2013 Atlantic basin hurricane season will be primarily determined by the strength of the THC/AMO and by the state of ENSO.

This paper also discusses how the US has been very fortunate to have a large and unexpected reduction in US landfalling hurricanes (particular major (Category 3-4-5) hurricanes) from what would be expected as a result of our having been in an active phase of the THC. When the THC is strong, the probability of landfalling major hurricanes along the Florida Peninsula and East Coast typically increases considerably.

For the 2013 hurricane season, we anticipate four possible scenarios with the probability of each as indicated on the next page:

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1. THC circulation becomes unusually strong in 2013 and no El Niño event occurs (resulting in a seasonal average net tropical cyclone (NTC) activity of ~ 180) – **20% chance**.

2. THC continues in the above-average condition it has been in since 1995 and no El Niño develops (NTC ~ 140) – **40% chance**.

3. THC continues in above-average condition it has been in since 1995 with the development of a significant El Niño (NTC ~ 75) – **35% chance**.

4. THC becomes weaker and there is the development of a significant El Niño (NTC ~ 40) – **5% chance**.

Typically, seasons with the above-listed NTC values have TC activity as follows:

180 NTC – 14-17 named storms, 9-11 hurricanes, 4-5 major hurricanes
140 NTC – 12-15 named storms, 7-9 hurricanes, 3-4 major hurricanes
75 NTC – 8-11 named storms, 3-5 hurricanes, 1-2 major hurricanes
40 NTC – 5-7 named storms, 2-3 hurricanes, 0-1 major hurricanes

Acknowledgment

This year's forecasts are funded by private and personal funds. We thank the GeoGraphics Laboratory at Bridgewater State University (MA) for their assistance in developing the United States Landfalling Hurricane Probability Webpage (available online at http://www.e-transit.org/hurricane).

The second author gratefully acknowledges the valuable input to his CSU seasonal forecast research project over many years by former graduate students and now colleagues Chris Landsea, John Knaff and Eric Blake. We also thank Professors Paul Mielke and Ken Berry of Colorado State University for much statistical analysis and advice over many years. We thank Bill Thorson for technical advice and assistance.

DEFINITIONS AND ACRONYMS

Accumulated Cyclone Energy (ACE) - A measure of a named storm's potential for wind and storm surge destruction defined as the sum of the square of a named storm's maximum wind speed (in 10^4 knots^2) for each 6-hour period of its existence. The 1950-2000 average value of this parameter is 96 for the Atlantic basin.

Atlantic Multi-Decadal Oscillation (AMO) – A mode of natural variability that occurs in the North Atlantic Ocean and evidencing itself in fluctuations in sea surface temperature and sea level pressure fields. The AMO is likely related to fluctuations in the strength of the oceanic thermohaline circulation. Although several definitions of the AMO are currently used in the literature, we define the AMO based on North Atlantic sea surface temperatures from 50-60°N, 10-50°W.

Atlantic Basin – The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño – A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3-7 years on average.

Hurricane (H) - A tropical cyclone with sustained low-level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day (HD) - A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or is estimated to have hurricane-force winds.

Madden Julian Oscillation (MJO) – A globally propagating mode of tropical atmospheric intra-seasonal variability. The wave tends to propagate eastward at approximately 5 ms^{-1}, circling the globe in roughly 40-50 days.

Main Development Region (MDR) – An area in the tropical Atlantic where a majority of major hurricanes form, which we define as 7.5-22.5°N, 20-75°W.

Major Hurricane (MH) - A hurricane which reaches a sustained low-level wind of at least 111 mph (96 knots or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale.

Major Hurricane Day (MHD) - Four 6-hour periods during which a hurricane has an intensity of Saffir/Simpson category 3 or higher.

Multivariate ENSO Index (MEI) – An index defining ENSO that takes into account tropical Pacific sea surface temperatures, sea level pressures, zonal and meridional winds and cloudiness.

Named Storm (NS) - A hurricane, a tropical storm or a sub-tropical storm.

Named Storm Day (NSD) - As in HD but for four 6-hour periods during which a tropical or sub-tropical cyclone is observed (or is estimated) to have attained tropical storm-force winds.

Net Tropical Cyclone (NTC) Activity –Average seasonal percentage mean of NS, NSD, H, HD, MH, MHD. Gives overall indication of Atlantic basin seasonal hurricane activity. The 1950-2000 average value of this parameter is 100.

Oceanic Nino Index (ONI) – Three-month running mean of SST in the Nino 3.4 region (5°N-5°S, 120°-170°W).

Saffir/Simpson Scale – A measurement scale ranging from 1 to 5 of hurricane wind and ocean surge intensity. One is a weak hurricane; whereas five is the most intense hurricane.

Southern Oscillation Index (SOI) – A normalized measure of the surface pressure difference between Tahiti and Darwin. Low values typically indicate El Niño conditions.

Sea Surface Temperature – SST

Sea Surface Temperature Anomaly – SSTA

Thermohaline Circulation (THC) – A large-scale circulation in the Atlantic Ocean that is driven by fluctuations in salinity and temperature. When the THC is stronger than normal, the AMO tends to be in its warm (or positive) phase, and more Atlantic hurricanes typically form.

Tropical Cyclone (TC) - A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels; including hurricanes, tropical storms and other weaker rotating vortices.

Tropical North Atlantic (TNA) index – A measure of sea surface temperatures in the area from 5.5-23.5°N, 15-57.5°W.

Tropical Storm (TS) - A tropical cyclone with maximum sustained winds between 39 mph (18 ms^{-1} or 34 knots) and 73 mph (32 ms^{-1} or 63 knots).

Vertical Wind Shear – The difference in horizontal wind between 200 mb (approximately 40000 feet or 12 km) and 850 mb (approximately 5000 feet or 1.6 km).

1 knot = 1.15 miles per hour = 0.515 meters per second

1 Introduction

This is the 30th year in which the CSU Tropical Meteorology Project has made forecasts of the upcoming season's Atlantic basin hurricane activity. Our research team has shown that a sizable portion of the year-to-year variability of Atlantic tropical cyclone (TC) activity can be hindcast with skill exceeding climatology. These forecasts are based on a statistical methodology derived from 30-60 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by our statistical analyses. These evolving forecast techniques are based on a variety of climate-related global and regional predictors previously shown to be related to the forthcoming seasonal Atlantic basin TC activity and landfall probability. We believe that seasonal forecasts must be based on methods that show significant hindcast skill in application to long periods of prior data. It is only through hindcast skill that one can demonstrate that seasonal forecast skill is possible. This is a valid methodology provided that the atmosphere continues to behave in the future as it has in the past.

The best predictors do not necessarily have the best individual correlations with hurricane activity. The best forecast parameters are those that explain the portion of the variance of seasonal hurricane activity that is not associated with the other forecast variables. It is possible for an important hurricane forecast parameter to show little direct relationship to a predictand by itself but to have an important influence when included with a set of 2-3 other predictors.

A direct correlation of a forecast parameter may not be the best measure of the importance of this predictor to the skill of a 2-3 parameter forecast model. This is the nature of the seasonal or climate forecast problem where one is dealing with a very complicated atmospheric-oceanic system that is highly non-linear. There is a maze of changing physical linkages between the many variables. These linkages can undergo unknown changes from weekly to decadal time scales. It is impossible to understand how all these processes interact with each other. No one can completely understand the full complexity of the atmosphere-ocean system. But, it is still possible to develop a reliable statistical forecast scheme which incorporates a number of the climate system's non-linear interactions. Any seasonal or climate forecast scheme must show significant hindcast skill before it is used in real-time forecasts.

2 Previous Extended-Range Early December Statistical Forecasts

Our seasonal hurricane forecast schemes issued in early June and early August have shown significant real-time skill since they began being issued in 1984. Our early April forecasts have also begun to show significant forecast skill in recent years. Our early December forecasts did not show skill in real-time forecast mode from 1992-2011, and we suspended them beginning last year. See Klotzbach and Gray (2011) for a full discussion of the lack of skill of real-time predictions from early December

Over the next few pages, we discuss two large-scale physical features which we know are fundamental for how active the 2013 Atlantic hurricane season is likely to be.

3 The Atlantic Ocean Thermohaline Circulation (THC) or the Atlantic Multi-Decadal Oscillation (AMO)

THEORY OF THC (OR AMO) INFLUENCE ON ATLANTIC HURRICANE VARIABILITY

The longer-period SST changes which the Atlantic Ocean experiences are due primarily to variations in the strength of the southwest to northeast upper branch of the THC in the high latitude Atlantic. The THC (which is observed and modeled to vary considerably in strength on multi-decadal timescales) is strong when there is an above-average poleward advection of warm tropical waters to the high latitudes of the Atlantic. This poleward-moving water can then sink to deep levels if it has high enough salinity content. This sinking process has been termed North Atlantic Deep Water Formation (NADWF). The submerged deep water then moves southward at deep levels in the Atlantic into the Southern Hemisphere. The amount of North Atlantic water that sinks is roughly proportional to the waters' density which at high latitudes, where water temperatures are low, is primarily dependent on salinity content. The strong association between North Atlantic SSTA and North Atlantic salinity is shown in Figure 1. High salinity implies higher rates of NADWF.

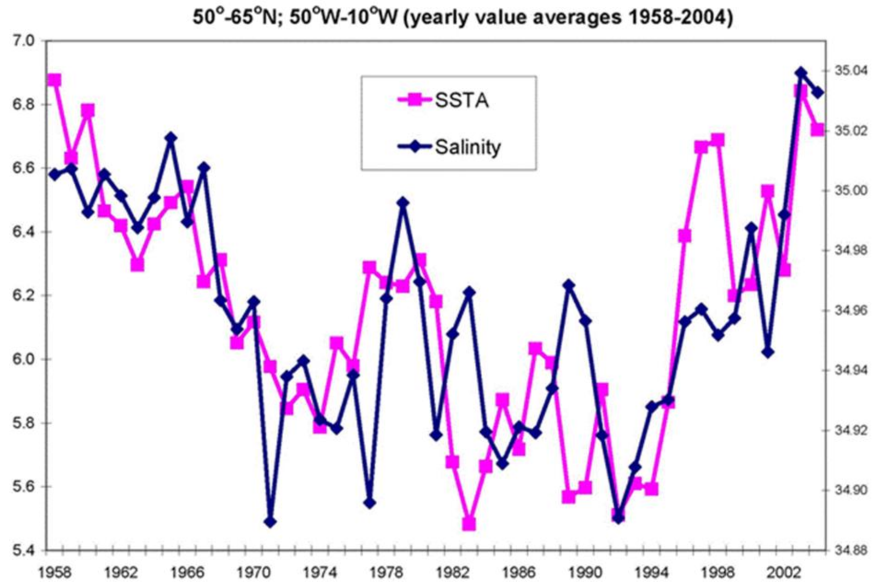

Figure 1: Illustration of the strong association of yearly average North Atlantic SSTA and North Atlantic salinity content between 1958 and 2004.

Through a progression of associations the strength of the NADWF is hypothesized to bring about alterations of the tropospheric vertical wind shear, trade wind strength, SSTs, middle-level water vapor, and other conditions in the Atlantic Main

Development Region (MDR – 7.5-22.5°N; 20-75°W). Changes of SST in the MDR are a consequence of a combination of the THC's influences on a variety of other parameters in the MDR (Figure 2). A stronger than average THC causes more ocean sinking in area 1. This in turn reduces the strength of the Atlantic gyre. There is then a change in all of the other conditions shown in Figure 2 to bring about more favorable parameters in the MDR for TC formation and intensification. This figure illustrates how the changing rate of southward advection of cold water in the east Atlantic (2) brings about alterations of SLP (3), SST (4), and rainfall (5). These changes in turn lead to changes in trade wind strength (6) and 200 mb zonal wind (7). Increases in hurricane activity and especially major hurricane activity follow (8). It is also found that in periods with a strong THC, El Niño frequency and intensity is typically reduced (9) and tropical South Atlantic SSTs are decreased (10).

The influence of the warmer Atlantic SST is not primarily to enhance lapse rates and Cb convection in the MDR but to act as a net overall positive or negative influence on a combination of parameters that must all change in a positive way to enhance MDR TC activity. These features typically all go together as a package to either enhance or to inhibit TC formation and/or TC intensity change (Figure 3). The simple argument of increasing or decreasing SST alone, without other important parameter changes is not typical of what we observe with TC activity variation in this region.

Higher rates of NADWF require stronger northward moving west Atlantic replacement water which is typically warmer, and if the stronger poleward flow is to continue, the replacement water must be of higher salinity content and consequently of higher density when such water cools toward freezing. Salinity dominates over water temperature when water temperatures are in the range of 0-7°C.

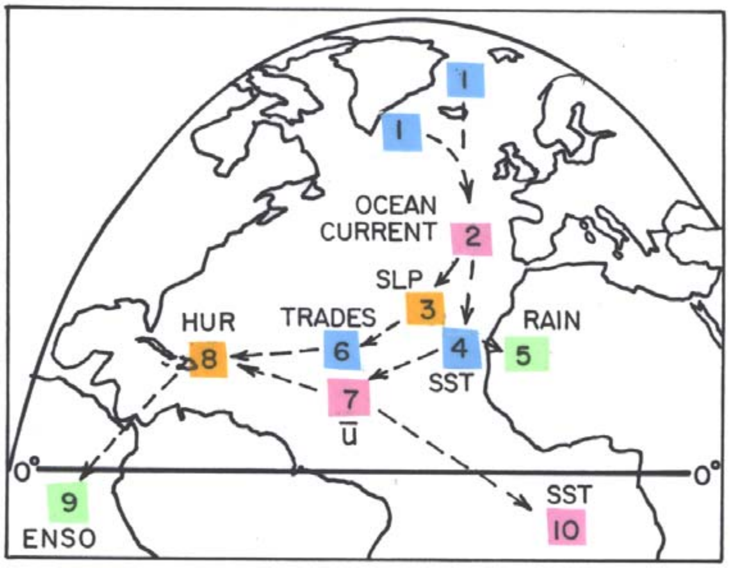

Figure 2: Idealized analysis of how changes in North Atlantic SST and salinity (area 1) lead to progressive ocean current, wind, pressure, SST, vertical shear or rain changes as portrayed in nine areas. It is this complete package of Atlantic/eastern Pacific meteorological parameter changes on a multi-decadal time scale which cause large changes in Atlantic major hurricanes on this time scale.

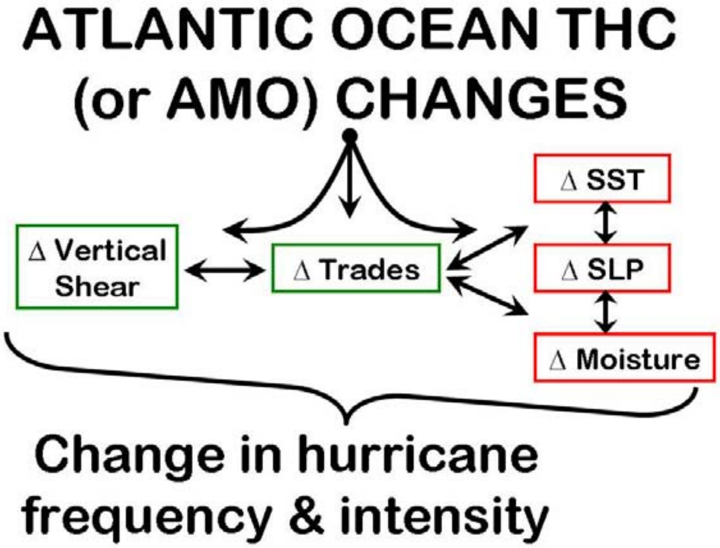

Figure 3: Idealized portrayal of how changes in the Atlantic THC bring about various parameter changes in the Atlantic's MDR between 7.5-22.5°N; 20-75°W. Vertical shear, trade-wind strength, and SST are the key parameters which respond to the THC changes. Favorable SLPA and mid-level moisture changes occur in association with the shear, trade wind, and SST changes. It is the THC's ability to affect a favorable alteration of a combination of these parameters within the MDR which leads to such a strong association between the strength of the THC and major hurricane frequency.

One of the primary physical drivers for active versus inactive Atlantic basin hurricane seasons is the strength of the THC or AMO (Goldenberg et al. 2001, Klotzbach and Gray 2008). A positive phase of the AMO (or strong phase of the THC) typically leads to 3-5 times more major Atlantic basin hurricane activity than does a negative phase. The typical period of the THC is about 60 years, with the period length varying between as short as 40-50 years and as long as 70-80 years. This means that we typically have 25-35 years of above-average Atlantic basin major TC activity and similar length periods with considerably reduced amounts of major TC activity. Strong THC or positive AMO conditions are characterized by positive SSTA and salinity content in the North Atlantic, increased rainfall in the Sahel region of Africa, warmer tropical Atlantic SST, reduced sea level pressure in the tropical Atlantic, reduced ENSO frequency and a wide variety of other physical processes. It is not specifically one parameter, such as tropical Atlantic SST, which is dominant but rather the combination of 4-5 parameters which all change sign together in a manner acting to either enhance or reduce Atlantic major hurricane activity.

While the THC typically remains in an above-average or in a below-average stage for periods of 25-35 years, there can be monthly, seasonal or longer breaks up to a year or two within these longer periods when the AMO (or THC) conditions of features such as SST, salinity, pressure, wind, and moisture become substantially weaker in positive phases or stronger during negative phases. During these periods where the multi-decadal signal is interrupted, we sometimes observe below-average TC activity during a positive phase (e.g., 1962 and 1968) or above-average TC activity during a negative phase (e.g., 1988 and 1989).

4 ENSO

We currently have neutral ENSO conditions in place over the tropical Pacific. A weak to moderate La Niña event during the winter of 2011/2012 rapidly warmed during the spring and into the early summer. Several indices including the Multivariate Enso Index (MEI) (Wolter and Timlin 1998) briefly registered El Niño conditions. Since that time, ENSO has moved back to a neutral state.

One of the important questions for the upcoming hurricane season is whether El Niño will develop for the 2013 hurricane season. Table 1 displays years since 1950 with similar September-October MEI values to 2012 (from -0.25 to 0.25 standard deviations of normal). Also displayed are the following year's August-September MEI values. Of the twelve years with similar MEI values to late 2012, five (42%) experienced El Niño conditions (defined as an August-September MEI greater than 0.5 standard deviations above normal) the following year. In addition, we have now gone since 2009 without an El Niño. Typically, warm ENSO events occur about 3-7 years.

Given this analysis, there is significant uncertainty in exactly what ENSO conditions will look like next year. Most statistical and dynamical forecast models indicate that neutral conditions will persist through the winter (Figure 4), with the majority of forecast models continuing to predict neutral conditions for the upcoming spring in the Nino 3.4 region (5°S-5°N, 120°-170°W). The ECMWF model appears to be somewhat more aggressive at warming during the spring months than several of the other forecasts, with several ensemble members indicating SSTs exceeding 0.5°C by May for the Nino 3.4 region (Figure 5). In general, this model has the highest levels of skill at predicting ENSO events, and consequently, there appears to be some likelihood that an El Niño will develop next year. We will be closely monitoring ENSO conditions over the next few months and will have more to say with our early April update.

Table 1: Years with September-October MEI values between -0.25 and 0.25 standard deviations, and the following year's August-September MEI values. Five of the twelve years had El Niño develop by the later part of the following summer. The correlation between the September-October MEI and the following year's August-September MEI is near zero.

Year	September-October MEI	Following Year's August-September MEI
1953	0.1	-1.2
1958	0.2	0.1
1959	-0.1	-0.5
1966	0.0	-0.6
1978	0.0	0.8
1980	0.2	0.2
1981	0.1	1.8
1983	0.0	-0.1
1984	0.0	-0.5
1985	-0.1	1.2
1990	0.2	0.7
2005	-0.2	0.8
Average	**0.0**	**0.2**
2012	0.1	

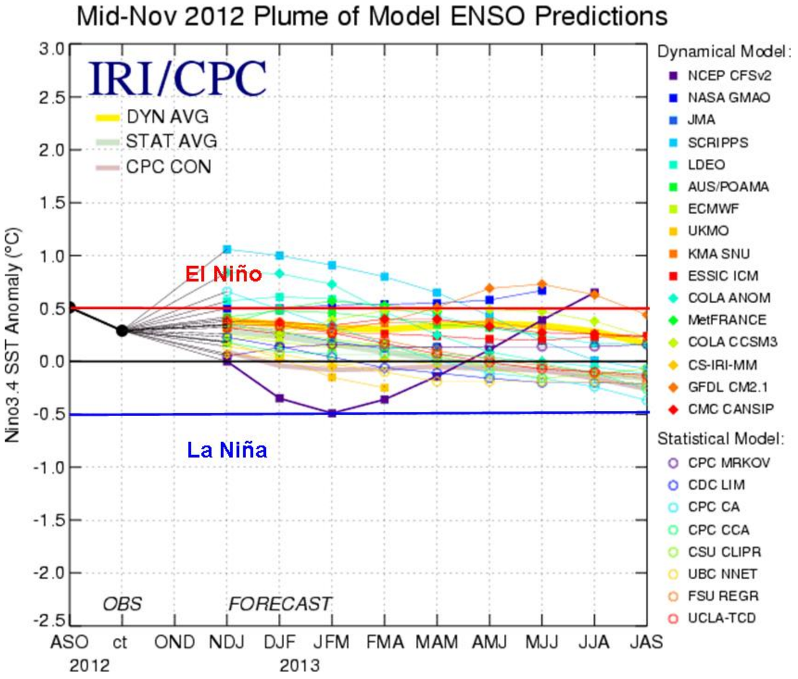

Figure 4: ENSO forecasts from various statistical and dynamical models. Figure courtesy of the International Research Institute (IRI).

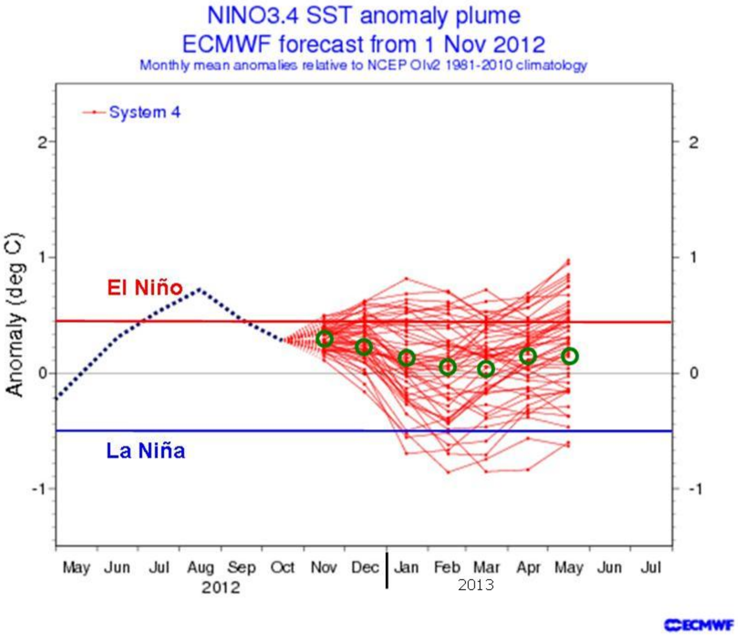

Figure 5: Scatterplot of ECMWF system 4 ensemble members for the Nino 3.4 region. Note that approximately 1/3 of ensemble members are predicting El Niño conditions by May. The green circle indicates the approximate midpoint of ensemble members.

5 Atlantic Basin Sea Surface Temperatures

Tropical Atlantic SSTs have warmed considerably since the spring of 2012, and currently stand at well above-average levels (Figure 6). Warm anomalies persist across the tropical Atlantic and far North Atlantic, indicative of an active phase of the AMO and a strong phase of the THC.

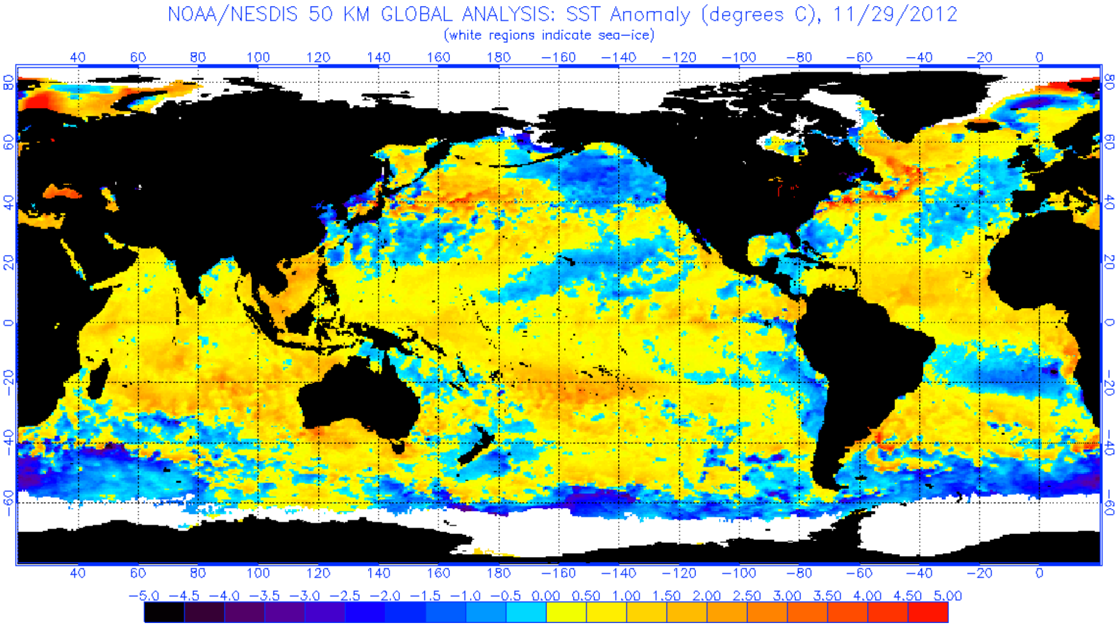

Figure 6: Currently-observed global SST anomalies.

One big question is how the anomalies in the tropical Atlantic will change over the next several months. During the winter of 2011/2012, the North Atlantic Oscillation (NAO) became strongly positive, which triggered the development of strong trades that cooled the tropical Atlantic considerably. Since that time, the NAO has consistently been negative, implying weak trades and leading to a significant warming of the tropical Atlantic. Figure 7 displays the trend in the NAO over the past year.

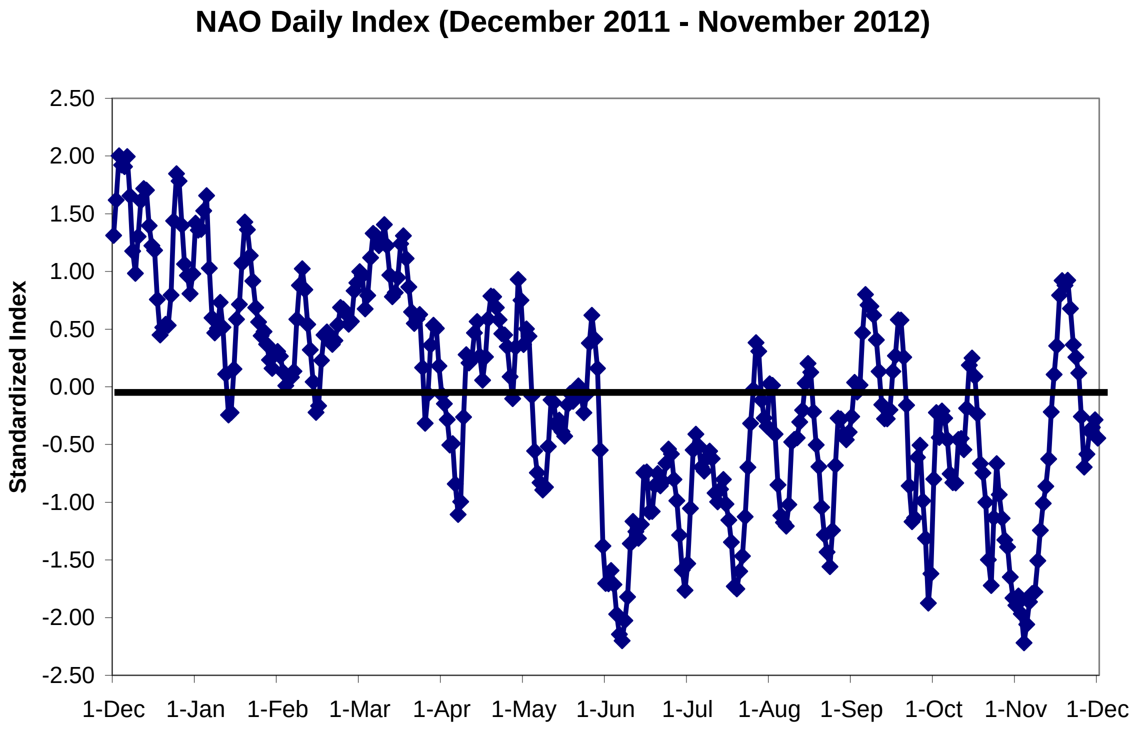

Figure 7: Daily NAO index from 1 December 2011 - 30 November 2012. The NAO was strongly positive from December 2011 - April 2012, and has generally been negative since that time.

6 Qualitative 2013 Hurricane Outlook Summary

Two of the major influences that need to be monitored during the winter of 2012/2013 are the state of ENSO and the strength of the AMO (THC). As mentioned in our discussion, we believe that we remain in an active era for Atlantic basin tropical cyclones, and consequently, if El Niño does not develop, an active 2013 season is likely. However, given our current statistical analysis, it appears that there is a moderate chance (30-50%) that El Niño will develop for the 2013 Atlantic basin hurricane season. By early April of next year, we should have a better idea of the likelihood of ENSO developing. Both dynamical and statistical ENSO forecast models show significantly improved skill for an August-October forecast by early spring.

The following calculations assume that we remain in a strong phase of the THC (positive phase of the AMO) for the 2013 Atlantic hurricane season. Table 2 displays the median season experienced during an active phase of the THC (1950-1969, 1995-2012). Also included are the median active THC years when an El Niño takes place, along with the median for all other years where either neutral or La Niña conditions are present. For this analysis, we define El Niño to be when the August-October Nino 3.4 index is greater than or equal to 0.5°C.

Table 2: Strong or active THC median tropical cyclone values, active THC El Niño tropical cyclone values and all other active THC years.

Forecast Parameter	Active THC (All Years)	Active THC (El Niño)	Active THC (La Niña or Neutral ENSO)
Named Storms (NS)	12.0	10.0	12.0
Named Storm Days (NSD)	64.3	52.8	70.8
Hurricanes (H)	7.0	5.0	7.0
Hurricane Days (HD)	31.0	26.0	32.8
Major Hurricanes (MH)	3.0	2.0	3.0
Major Hurricane Days (MHD)	7.3	6.5	9.5
Accumulated Cyclone Energy (ACE)	121	84	125
Net Tropical Cyclone Activity (NTC)	134	86	140

For comparison, we now provide a similar analysis for the inactive phase of the THC (1970-1994). Table 3 displays the median for all inactive THC years, inactive THC years when an El Niño takes place, and the median for all other years where either neutral or La Niña conditions are present. Note how much lower the statistics are for all three columns, especially for El Niño years. An additional interesting fact is that the median El Niño year in an active THC phase is comparable to a non-El Niño year in an inactive THC phase.

Table 3: The weak or inactive THC median tropical cyclone values, inactive THC El Niño tropical cyclone values and all other inactive THC years.

Forecast Parameter	Inactive THC (All Years)	Inactive THC (El Niño)	Inactive THC (La Niña or Neutral ENSO)
Named Storms (NS)	9.0	7.0	11.0
Named Storm Days (NSD)	40.5	28.8	46.1
Hurricanes (H)	5.0	3.0	5.0
Hurricane Days (HD)	14.3	7.3	19.4
Major Hurricanes (MH)	1.0	1.0	2.0
Major Hurricane Days (MHD)	1.0	0.5	2.9
Accumulated Cyclone Energy (ACE)	68	36	80
Net Tropical Cyclone Activity (NTC)	80	38	87

At this extended lead time when ENSO forecasts have little skill, we expect to see an active season (in keeping with the median of the right-hand column in Table 2) unless an El Niño develops. In that case, we would expect to see activity more in line with the third column of Table 2. At this point, we do not expect the THC to weaken substantially for the 2013 Atlantic hurricane season, but if that were the case, we would expect activity more in line with the median values listed in Table 3.

With our forecast issued in early April, we will also provide landfall probabilities for the United States coastline and the Caribbean. On a statistical basis, more active tropical cyclone seasons tend to have more landfalling hurricanes. Lastly, we reiterate the outlook discussed in our abstract as our best estimate for the 2013 Atlantic hurricane season:

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1. THC circulation becomes unusually strong in 2013 and no El Niño event occurs (resulting in a seasonal average net tropical cyclone (NTC) activity of ~ 180) – **20% chance**.

2. THC continues in the above-average condition it has been in since 1995 and no El Niño develops (NTC ~ 140) – **40% chance**.

3. THC continues in above-average condition it has been in since 1995 with the development of a significant El Niño (NTC ~ 75) – **35% chance**.

4. THC becomes weaker and there is the development of a significant El Niño (NTC ~ 40) – **5% chance**.

Typically, seasons with the above-listed NTC values have TC activity as follows:

180 NTC – 14-17 named storms, 9-11 hurricanes, 4-5 major hurricanes
140 NTC – 12-15 named storms, 7-9 hurricanes, 3-4 major hurricanes
75 NTC – 8-11 named storms, 3-5 hurricanes, 1-2 major hurricanes
40 NTC – 5-7 named storms, 2-3 hurricanes, 0-1 major hurricanes

6 Dearth of Expected U.S. Major Hurricane Landfall Since 1995 (Except for 2004 and 2005)

The United States has been very fortunate during the recent 18-year active period as regards major hurricane landfall (1995-2012), when the Atlantic thermohaline circulation (THC) has been strong. Other than the 2004-2005 seasons, the United States has had only three major hurricane landfalls. Approximately 80-85 percent of tropical cyclone-related damage is due to major hurricanes, when damage is normalized by population, inflation and wealth per capita (Pielke and Landsea 1998, Pielke et al. 2008). In the last 100 years, approximately 30% of all major hurricanes that form in the Atlantic basin make United States landfall. Over the 18-year period from 1995-2012, we have had a total of 65 major hurricanes. Of these 65 major hurricanes, only 10 have made United States landfall as major hurricanes (15%), or approximately half of what we would expect given the long-term average. When we exclude the two very active major hurricane landfall years of 2004-2005 (7 major hurricanes making U.S. landfall out of 13 total major hurricanes that formed in the Atlantic basin), only three of the 53 major hurricanes that formed in the Atlantic basin from 1995-2003 and 2006-2012 have made

U.S. landfall (Figure 8). This is significantly fewer than made landfall during the very active 16-year period of 1949-1964, when 14 of 60 Atlantic basin major hurricanes made US landfall (Figure 9). This is a 14 to 3 or nearly 5 to 1 difference. This string of good luck cannot be expected to continue in the future.

This string of good luck has been even more remarkable for the Florida Peninsula and the East Coast. From 1995-2012, only four major hurricanes out of 66 (6%) that formed in the Atlantic basin have made landfall along the Florida Peninsula/East Coast. The 20th century average is that approximately 18% of all major hurricanes that form in the Atlantic basin make Florida Peninsula/East Coast landfall. There has been a three times reduction in the number of major hurricanes making Florida Peninsula/East Coast landfall during the most recent active period when compared with the 20th century average.

More impressive signals can be seen if one excludes the 2004-2005 hurricane seasons, when three major hurricanes made landfall along the Florida Peninsula and East Coast. From 1941-1969 and 2004-2005, 24 major hurricanes made landfall along the Florida Peninsula/East Coast over 31 years, or 0.77 major hurricane landfalls per year (Figure 10). This compares with the 1970-2012 (excluding 2004-2005) average when an average of only 0.13 major hurricane landfalls per year occurred (or approximately six times fewer landfalls per year during the more recent period) (Figure 11).

This dearth in United States major hurricane landfalls in more recent years has resulted in much lower damages being sustained along the coastline than would be expected given the heightened amounts of basinwide activity that have been experienced since 1995.

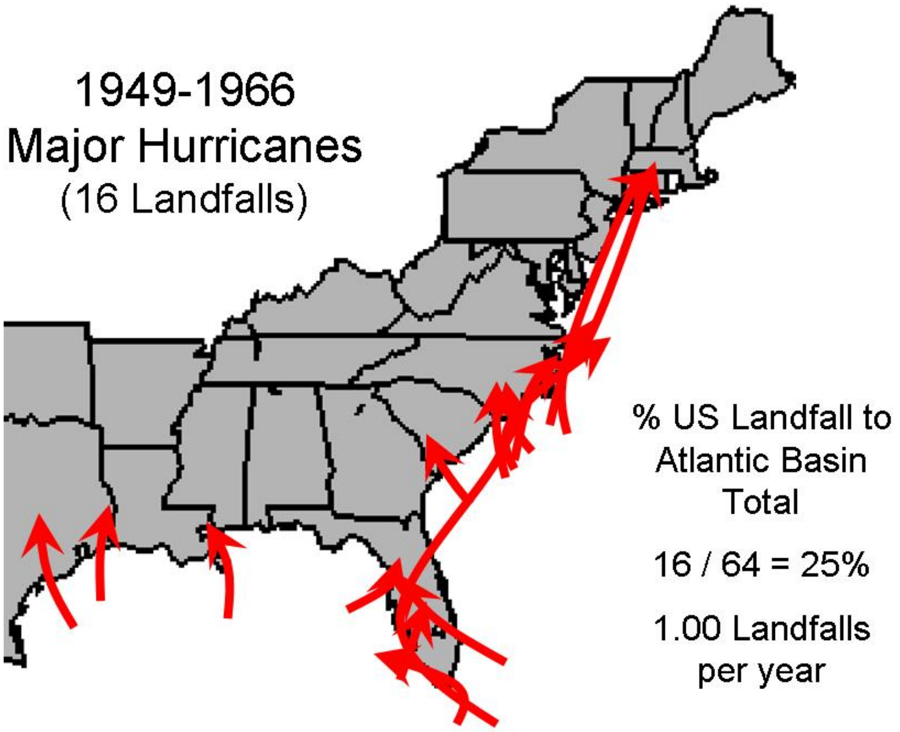


Figure 8: United States major hurricane landfalls from 1949-1966.

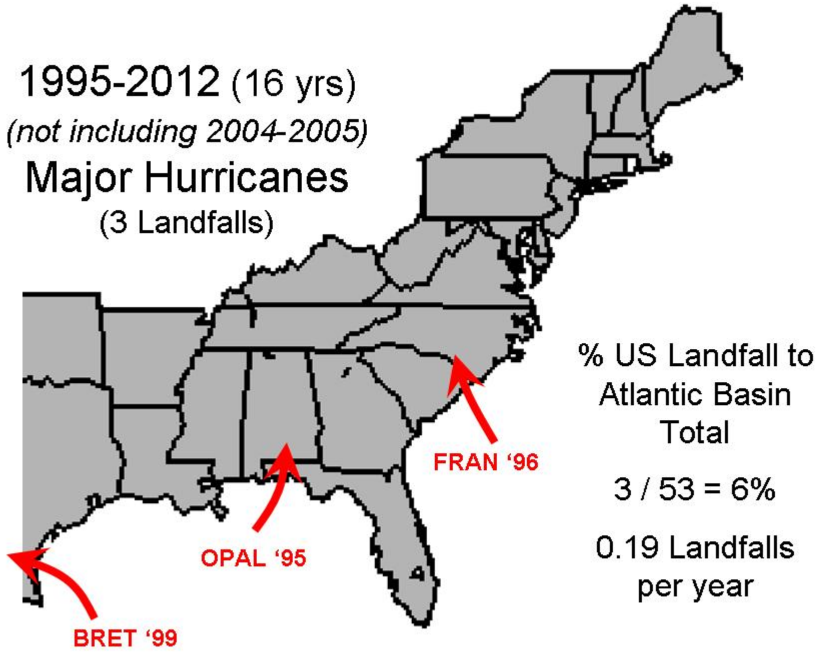


Figure 9: United States major hurricane landfalls from 1995-2012 (excluding 2004-2005).

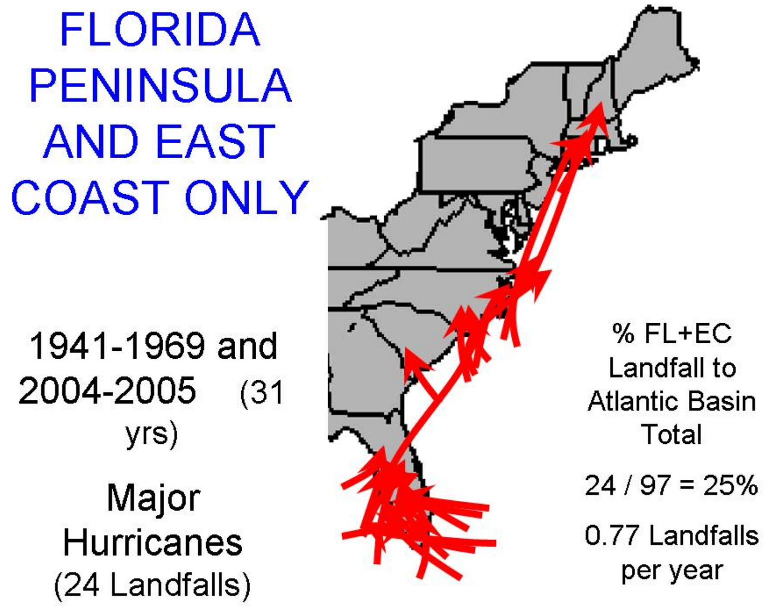


Figure 10: Florida Peninsula and East Coast major hurricane landfalls from 1941-1969 and 2004-2005.

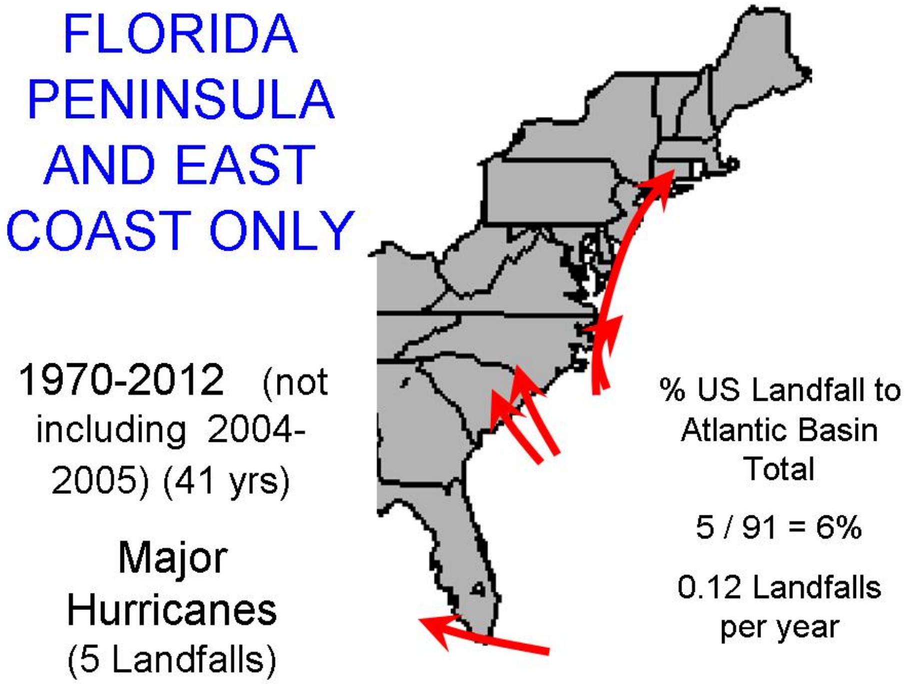


Figure 11: Florida Peninsula and East Coast major hurricane landfalls from 1970-2012 (excluding 2004-2005).

US Especially Fortunate over the Past Seven Years

The U.S. has been especially lucky over the past seven years (2006-2012) in that no major hurricanes have made landfall. Following the very active landfalling seasons of 2004-2005, when seven of 13 major hurricanes made U.S. landfall, none of the twenty major hurricanes forming in the Atlantic basin in the past six years have impacted the U.S. coastline at major hurricane strength. The last 100-year climatology indicates that approximately 30% of all major hurricanes that form in the Atlantic basin make U.S. landfall as major hurricanes.

The primary reason why we believe that the U.S. has been so fortunate is due to mid-level steering currents that have in recent years tended to steer storms away from the U.S. Figure 12 displays the August-September 500-mb U.S. and western Atlantic upper-level height field for 2006-2012 minus the height field for 2004-2005. Note the anomalous troughing along the U.S. East Coast in 2006-2012 compared to 2004-2005. This pattern caused the major hurricanes forming during the past seven years to recurve before they could hit the U.S. coastline. This anomalous trough is part of a larger mid-latitude ridge/trough wave pattern that has tended to be in place over the past seven years (Figure 13).

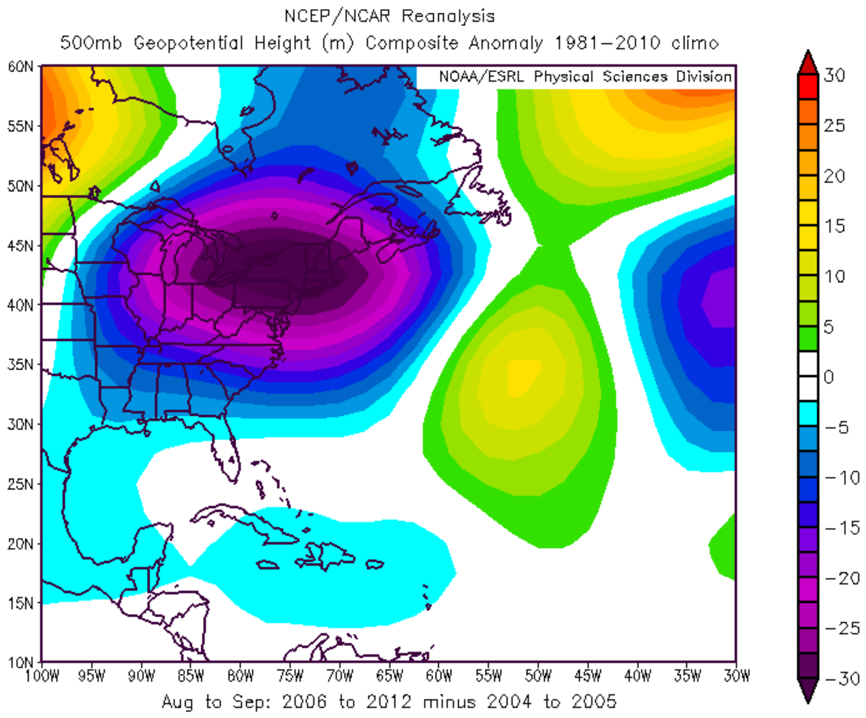


Figure 12: Average 500-mb height pattern difference of 2006-2012 minus 2004-2005. Note the anomalous troughing that has prevailed along the U.S. East Coast, causing systems to recurve before they could impact the U.S. mainland.

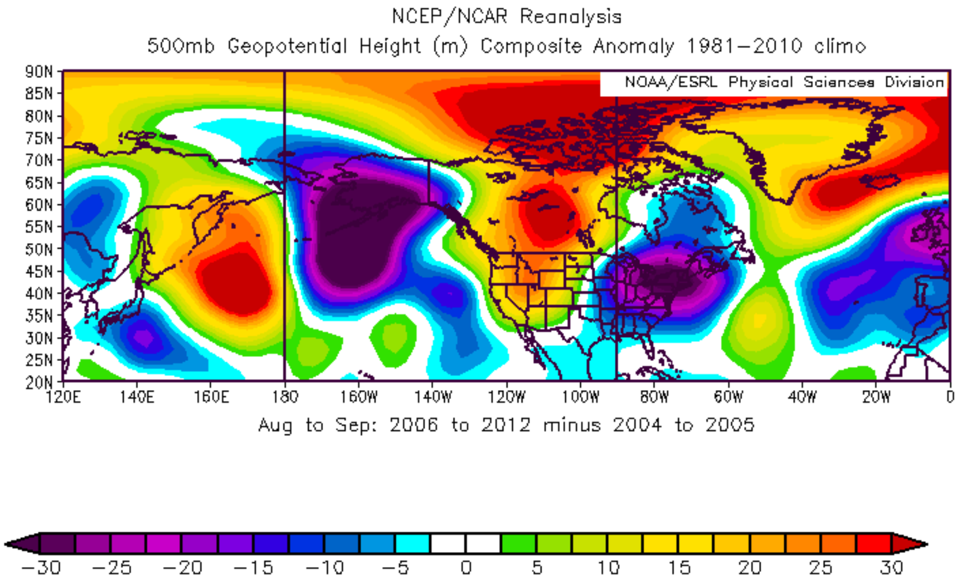


Figure 13: Average 500-mb August-September height pattern difference of 2006-2012 minus 2004-2005 for most of the Northern Hemisphere. Note the anomalous ridge/trough pattern differences that extend all the way from eastern Asia to western Europe.

Unfortunately, very strong ridging developed over most of the North Atlantic in late October. This strong ridging combined with a strong mid-latitude trough to create the highly anomalous steering flow that directed Sandy north and then westward into New Jersey. See the discussion by Gray and Klotzbach (2012) for a much more extensive discussion of Sandy.

THC Relationship with Gulf Coast vs. Florida Peninsula and East Coast Landfalls

We find that the strength of the THC imparts a significant variation in the number of major hurricane landfalls, especially along the Florida Peninsula and East Coast (FL+EC) (Regions 5-11) compared with the Gulf Coast (Regions 1-4). When the THC is strong, there are substantially more landfalls along the FL+EC compared with the Gulf Coast. When the THC is weak, the situation is reversed, with many more landfalls along the Gulf Coast compared with the FL+EC. Figure 14 and Table 4 portray in more detail the large differences in Gulf vs. FL+EC major hurricane landfall events as a function of a strong or weak THC.

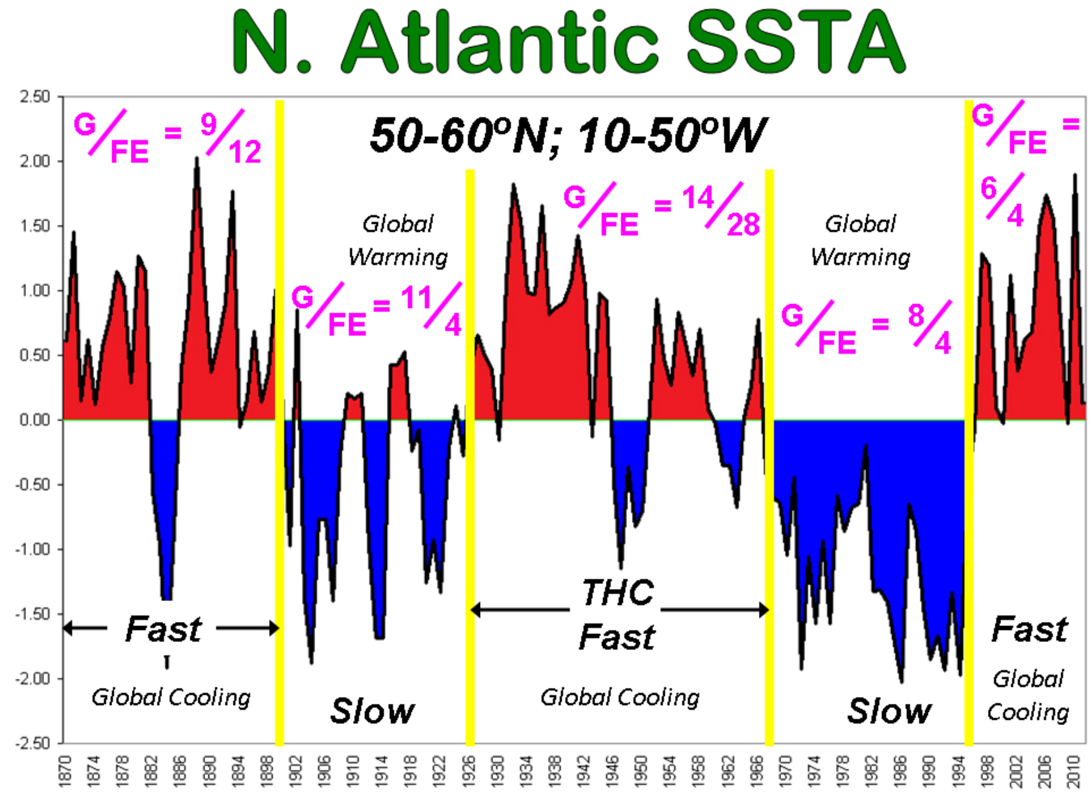


Figure 14: North Atlantic sea surface temperature anomalies (SSTAs) from 1870-2010, along with landfalling major hurricanes for each fast (active) vs. slow (inactive) THC period. Note how the ratio differences shifts between the Gulf Coast (G) and the Florida Peninsula and East Coast (FE). The ratio has not been as expected with the most recent fast THC period, where Gulf Coast major hurricane landfalls have continued to predominate.

Table 4: Number of major hurricane (MH) landfalls along the US Gulf Coast (Regions 1-4) and along the Florida Peninsula and the East Coast (Regions 5-11) (parentheses gives number per year).

Years	*THC (Years)*	*Gulf Coast Region 1-4*	*FL + EC Region 5-11*	*Total*
1900-1925	Weak (26)	11 (0.42)	4 (0.15)	15 (0.58)
1926-1969	Strong (44)	14 (0.32)	28 (0.64)	42 (0.95)
1970-1994	Weak (25)	8 (0.32)	4 (0.16)	12 (0.48)
1995-2012	Strong (18)	6 (0.33)	4 (0.22)	10 (0.56)
TOTAL	**(113)**	**39 (0.35)**	**40 (0.35)**	**89 (0.79)**
Total Strong THC Years	(62)	20 (0.32)	32 (0.52)	52 (0.84)
Total Weak THC Years	(51)	19 (0.37)	8 (0.16)	26 (0.51)
Ratio of per year Strong vs. Weak THC Years		0.86	3.25	1.65

During 51 of the last 113 years (1900-1925 and 1970-1994) when we diagnose that the THC was weak, there were 27 major hurricanes (0.53 per year) that made landfall along the US coastline. Of these 27 major hurricanes, 19 (or 70% of them) made landfall along the Gulf Coast and only 8 (or 30%) made landfall on the Florida Peninsula or along the East Coast (FL+EC). This 51-year period also saw only 32% as much Atlantic basin major hurricane activity and 29% as much major hurricane day activity as did the other 62 years when the THC was strong

By contrast, during the 62 years when we diagnose the THC to be strong (1926-1969 and 1995-2012), 52 major hurricanes (0.84 per year) made US landfall. Of these 52 major landfall events that occurred during these strong THC periods, 32 of them (or 62%) occurred along the FL+EC and 21 (or 38%) occurred along the Gulf Coast. Landfall along the FL+EC in active THC periods about matches the pickup in Atlantic basin NTC activity. During the weaker THC periods, the FL+EC MH landfall goes down somewhat more than does the net Atlantic basin MH number and MHDs.

For the whole period of the last 113 years (1900-2012) there have been a relatively similar number of Gulf Coast versus FL+EC major landfall events, with 41 occurring along the Gulf Coast and 47 along the FL+EC.

Except for the seven landfalling US major hurricanes (four along the Gulf Coast, and three along FL+EC) in the years of 2004-2005, it is very surprising that FL+EC have experienced only one major hurricane landfall since the beginning of the strong THC period in 1995 (Fran in 1996).

There were only two other landfalling major hurricanes in this 16-year period along the Gulf Coast (Opal 1995, Bret 1999).

During the 44-year period (1926-1969) when we judged the THC to have been strong, there were 42 US major hurricane strikes (0.95 per year). Of these 42, 28 were along FL+EC (0.64 per year) and 14 (0.32 per year) along the Gulf Coast. This is to be contrasted with only four major hurricane strikes along FL+EC in the last 18 years (0.22 per year). This is only 23 percent as many major landfall events as the average major hurricane landfall strikes during the earlier strong THC period of 1926-1969. If we disregard the unusual years of 2004-2005, we find that in the other 16 years since the recent strong THC period began in 1995, only one major hurricane strike (0.06 per year) has occurred. This is only 10% as many as during the previous strong THC period of 1926-1969.

7 Landfall Probabilities for 2013

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the U.S. coastline and in the Caribbean. While we are not issuing a quantitative forecast in this early outlook, we can still provide interested readers with the climatological probabilities of landfall for various portions of the United States coastline.

Table 5 lists climatological strike probabilities for the 2013 hurricane season for different TC categories for the entire U.S. coastline, the Gulf Coast and the East Coast including the Florida peninsula. We also issue probabilities for various islands and landmasses in the Caribbean and in Central America.

Table 5: Climatological probability (expressed in percent) of one or more landfalling tropical storms (TS), category 1-2 hurricanes (HUR), category 3-4-5 hurricanes, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (Regions 1-4), and along the Florida Peninsula and the East Coast (Regions 5-11). Probabilities of a tropical storm, hurricane and major hurricane tracking into the Caribbean are also provided.

Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	79%	68%	52%	84%	97%
Gulf Coast (Regions 1-4)	59%	42%	30%	60%	83%
Florida plus East Coast (Regions 5-11)	50%	44%	31%	61%	81%
Caribbean (10-20°N, 60-88°W)	82%	57%	42%	75%	96%

The second author broke down the United States coastline into eleven regions based upon climatological probabilities of landfall during the 20th century. Figure 15 displays landfalling TCs along the United States coastline from 1900-1999, along with the locations of the eleven landfall regions. The black line between Region 4 and 5 delineates our breakdown between the Gulf Coast and Florida Peninsula and East Coast regions.

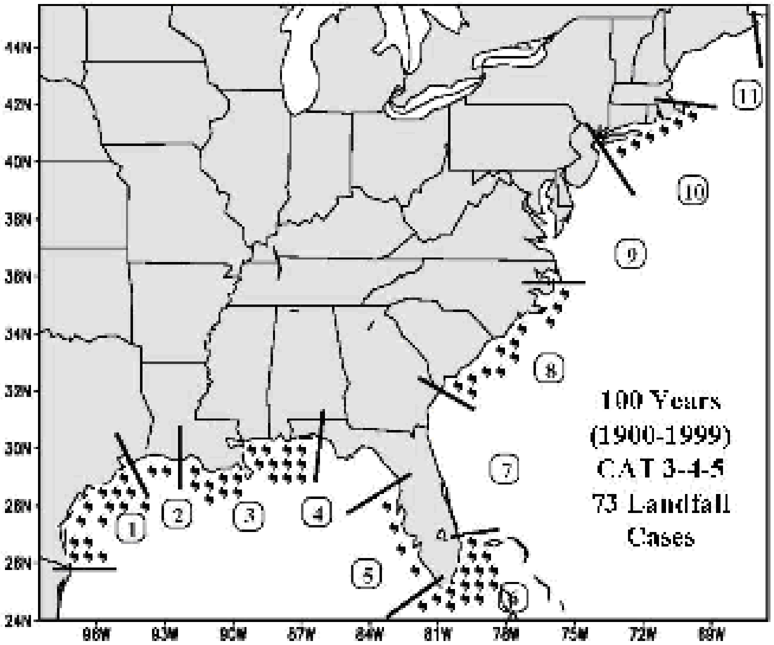


Figure 15: Eleven regions along the United States coastline which were created based upon the frequency of major hurricane landfall during the period from 1900-1999.

Table 6 displays the climatological probability of one or more named storms, hurricanes and major hurricanes making landfall in each of the eleven regions, based upon statistics since the late 19th century.

Table 6: Climatological probability of one or more named storms, hurricanes and major hurricanes making landfall in each of eleven regions.

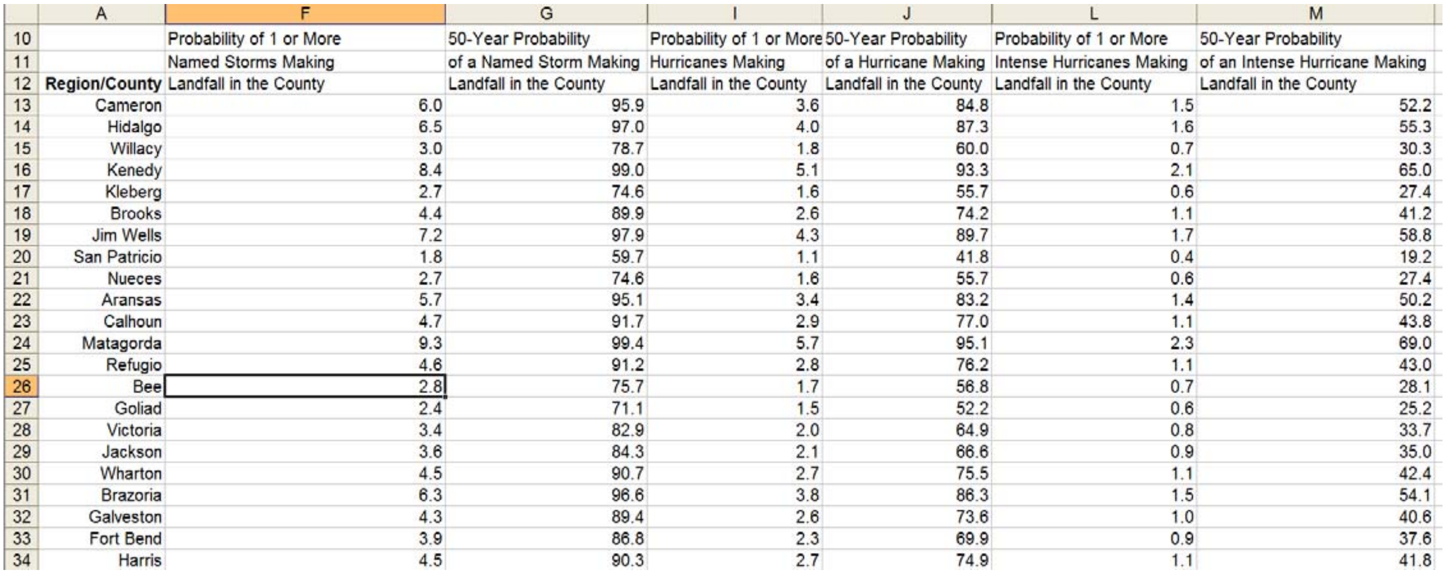
Region	Named Storm Probability	Hurricane Probability	Major Hurricane Probability
1	43%	29%	13%
2	19%	10%	3%
3	56%	33%	17%
4	29%	14%	2%
5	22%	8%	5%
6	37%	28%	14%
7	18%	8%	2%
8	41%	29%	9%
9	9%	3%	<1%
10	15%	9%	4%
11	6%	3%	<1%

More recently, we have also calculated probabilities of each state being impacted by a tropical cyclone, using the impacts database available from the National Hurricane Center. Table 7 displays the climatological probabilities for each state along the United States coastline being impacted by a hurricane and major hurricane, respectively.

Table 7: Climatological probability of each state along the United States coastline being impacted by a hurricane and major hurricane, respectively.

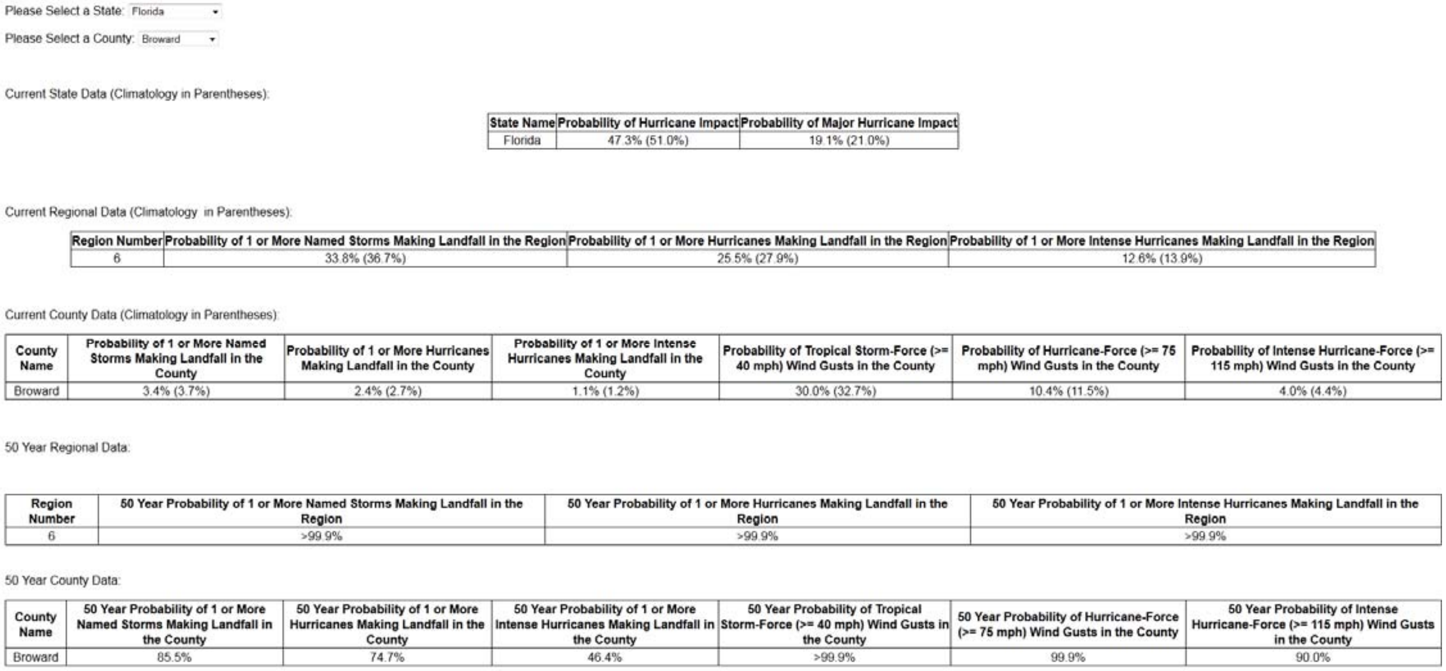
State	Hurricane	Major Hurricane
Texas	33%	12%
Louisiana	30%	12%
Mississippi	11%	4%
Alabama	16%	3%
Florida	51%	21%
Georgia	11%	1%
South Carolina	17%	4%
North Carolina	28%	8%
Virginia	6%	1%
Maryland	1%	<1%
Delaware	1%	<1%
New Jersey	1%	<1%
New York	8%	3%
Connecticut	7%	2%
Rhode Island	6%	3%
Massachusetts	7%	2%
New Hampshire	1%	<1%
Maine	4%	<1%

The Landfall Probability Website (http://www.e-transit.org/hurricane) has additional probability information including county-level probabilities for 205 coastal counties from Brownsville, Texas to Eastport, Maine. Figure 16 displays the climatological probabilities for all of the counties in Region 1, while Figure 17 displays more in-depth information based on the August 2012 seasonal forecast for Broward County, Florida.



	A	F	G	I	J	L	M
10		Probability of 1 or More	50-Year Probability	Probability of 1 or More	50-Year Probability	Probability of 1 or More	50-Year Probability
11		Named Storms Making	of a Named Storm Making	Hurricanes Making	of a Hurricane Making	Intense Hurricanes Making	of an Intense Hurricane Making
12	**Region/County**	Landfall in the County	Landfall in the County	Landfall in the County	Landfall in the County	Landfall in the County	Landfall in the County
13	Cameron	6.0	95.9	3.6	84.8	1.5	52.2
14	Hidalgo	6.5	97.0	4.0	87.3	1.6	55.3
15	Willacy	3.0	78.7	1.8	60.0	0.7	30.3
16	Kenedy	8.4	99.0	5.1	93.3	2.1	65.0
17	Kleberg	2.7	74.6	1.6	55.7	0.6	27.4
18	Brooks	4.4	89.9	2.6	74.2	1.1	41.2
19	Jim Wells	7.2	97.9	4.3	89.7	1.7	58.8
20	San Patricio	1.8	59.7	1.1	41.8	0.4	19.2
21	Nueces	2.7	74.6	1.6	55.7	0.6	27.4
22	Aransas	5.7	95.1	3.4	83.2	1.4	50.2
23	Calhoun	4.7	91.7	2.9	77.0	1.1	43.8
24	Matagorda	9.3	99.4	5.7	95.1	2.3	69.0
25	Refugio	4.6	91.2	2.8	76.2	1.1	43.0
26	Bee	2.8	75.7	1.7	56.8	0.7	28.1
27	Goliad	2.4	71.1	1.5	52.2	0.6	25.2
28	Victoria	3.4	82.9	2.0	64.9	0.8	33.7
29	Jackson	3.6	84.3	2.1	66.6	0.9	35.0
30	Wharton	4.5	90.7	2.7	75.5	1.1	42.4
31	Brazoria	6.3	96.6	3.8	86.3	1.5	54.1
32	Galveston	4.3	89.4	2.6	73.6	1.0	40.6
33	Fort Bend	3.9	86.8	2.3	69.9	0.9	37.6
34	Harris	4.5	90.3	2.7	74.9	1.1	41.8

Figure 16: Individual county probabilities for Region 1. Probabilities for every county along the United States coastline are listed in a similar fashion on the Landfall Probability Website.



Please Select a State: Florida

Please Select a County: Broward

Current State Data (Climatology in Parentheses):

State Name	Probability of Hurricane Impact	Probability of Major Hurricane Impact
Florida	47.3% (51.0%)	19.1% (21.0%)

Current Regional Data (Climatology in Parentheses):

Region Number	Probability of 1 or More Named Storms Making Landfall in the Region	Probability of 1 or More Hurricanes Making Landfall in the Region	Probability of 1 or More Intense Hurricanes Making Landfall in the Region
6	33.8% (36.7%)	25.5% (27.9%)	12.6% (13.9%)

Current County Data (Climatology in Parentheses):

County Name	Probability of 1 or More Named Storms Making Landfall in the County	Probability of 1 or More Hurricanes Making Landfall in the County	Probability of 1 or More Intense Hurricanes Making Landfall in the County	Probability of Tropical Storm-Force (>= 40 mph) Wind Gusts in the County	Probability of Hurricane-Force (>= 75 mph) Wind Gusts in the County	Probability of Intense Hurricane-Force (>= 115 mph) Wind Gusts in the County
Broward	3.4% (3.7%)	2.4% (2.7%)	1.1% (1.2%)	30.0% (32.7%)	10.4% (11.5%)	4.0% (4.4%)

50 Year Regional Data:

Region Number	50 Year Probability of 1 or More Named Storms Making Landfall in the Region	50 Year Probability of 1 or More Hurricanes Making Landfall in the Region	50 Year Probability of 1 or More Intense Hurricanes Making Landfall in the Region
6	>99.9%	>99.9%	>99.9%

50 Year County Data:

County Name	50 Year Probability of 1 or More Named Storms Making Landfall in the County	50 Year Probability of 1 or More Hurricanes Making Landfall in the County	50 Year Probability of 1 or More Intense Hurricanes Making Landfall in the County	50 Year Probability of Tropical Storm-Force (>= 40 mph) Wind Gusts in the County	50 Year Probability of Hurricane-Force (>= 75 mph) Wind Gusts in the County	50 Year Probability of Intense Hurricane-Force (>= 115 mph) Wind Gusts in the County
Broward	85.5%	74.7%	46.4%	>99.9%	99.9%	90.0%

Figure 17: In-depth county probabilities based on the August 2012 seasonal forecast for Broward County, Florida.

8 Have Atmospheric CO_2 Increases Been Responsible for the Recent Large Upswing (since 1995) in Atlantic Basin Major Hurricanes and Devastating US Hurricanes of Recent Years?

We strongly believe that the increases in atmospheric CO_2 since the start of the 20th century have had little or no significant effect on Atlantic basin or global TC activity as extensively discussed in our many previous forecast write-ups and recently in Gray (2011). Global tropical cyclone activity has shown no significant trend over the past thirty years.

We do not believe that Hurricane/Superstorm Sandy, or other destructive tropical cyclones of the past ten years (e.g., Ivan, Katrina, Rita, Wilma, Ike, etc.) are a direct consequence of human-induced global warming. Any impacts of climate change on hurricanes are believed to be quite small and within the noise level. A more complete discussion of Hurricane Sandy and climate change, along with a more in-depth discussion of trends in Atlantic basin TC activity are given in Gray and Klotzbach (2012).

9 Forthcoming Updated Forecasts of 2013 Hurricane Activity

We will be issuing seasonal updates of our 2013 Atlantic basin hurricane forecasts on **Wednesday April 10**, **Monday 3 June**, **and Friday 2 August**. We will also be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October. A verification and discussion of all 2013 forecasts will be issued in late November 2013. All of these forecasts will be available on the web at: http://hurricane.atmos.colostate.edu/Forecasts.

10 Acknowledgments

Besides the individuals named on page 3, there have been a number of other meteorologists that have furnished us with data and given valuable assessments of the current state of global atmospheric and oceanic conditions. These include Brian McNoldy, Art Douglas, Ray Zehr, Mark DeMaria, Todd Kimberlain, Paul Roundy and Amato Evan. In addition, Barbara Brumit and Amie Hedstrom have provided excellent manuscript, graphical and data analysis and assistance over a number of years. We have profited over the years from many in-depth discussions with most of the current and past NHC hurricane forecasters. The second author would further like to acknowledge the encouragement he has received for this type of forecasting research application from Neil Frank, Robert Sheets, Robert Burpee, Jerry Jarrell, Max Mayfield, and Bill Read former directors of the National Hurricane Center (NHC), and the current director, Rick Knabb.

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12 Verification of Previous Forecasts

Table 8: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity between 2008-2012.

2008	7 Dec. 2007	Update 9 April	Update 3 June	Update 5 August	Obs.
Hurricanes	7	8	8	9	8
Named Storms	13	15	15	17	16
Hurricane Days	30	40	40	45	29.50
Named Storm Days	60	80	80	90	84.75
Major Hurricanes	3	4	4	5	5
Major Hurricane Days	6	9	9	11	8.50
Accumulated Cyclone Energy	115	150	150	175	146
Net Tropical Cyclone Activity	125	160	160	190	164

2009	10 Dec. 2008	Update 9 April	Update 2 June	Update 4 August	Obs.
Hurricanes	7	6	5	4	3
Named Storms	14	12	11	10	9
Hurricane Days	30	25	20	18	11.25
Named Storm Days	70	55	50	45	27.25
Major Hurricanes	3	2	2	2	2
Major Hurricane Days	7	5	4	4	3.25
Accumulated Cyclone Energy	125	100	85	80	50
Net Tropical Cyclone Activity	135	105	90	85	66

2010	9 Dec. 2009	Update 7 April	Update 2 June	Update 4 August	Obs.
Hurricanes	6-8	8	10	10	12
Named Storms	11-16	15	18	18	19
Hurricane Days	24-39	35	40	40	37.50
Named Storm Days	51-75	75	90	90	88.25
Major Hurricanes	3-5	4	5	5	5
Major Hurricane Days	6-12	10	13	13	11
Accumulated Cyclone Energy	100-162	150	185	185	163
Net Tropical Cyclone Activity	108-172	160	195	195	195

2011	8 Dec. 2010	Update 6 April	Update 1 June	Update 3 August	Obs.
Hurricanes	9	9	9	9	7
Named Storms	17	16	16	16	19
Hurricane Days	40	35	35	35	25
Named Storm Days	85	80	80	80	90.50
Major Hurricanes	5	5	5	5	3
Major Hurricane Days	10	10	10	10	4.50
Accumulated Cyclone Energy	165	160	160	160	125
Net Tropical Cyclone Activity	180	175	175	175	137

2012	4 April	Update 1 June	Update 3 August	Obs.
Hurricanes	4	5	6	10
Named Storms	10	13	14	19
Hurricane Days	16	18	20	26
Named Storm Days	40	50	52	99.50
Major Hurricanes	2	2	2	1
Major Hurricane Days	3	4	5	0.25
Net Tropical Cyclone Activity	75	90	105	121