FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2016

We continue to foresee a near-average 2016 Atlantic hurricane season. ENSO is currently cool neutral, and the potential exists for weak La Niña conditions by the peak of the Atlantic hurricane season. While the tropical Atlantic is slightly warmer than normal, the far North Atlantic and subtropical eastern Atlantic are somewhat cooler than normal, potentially indicative of a negative phase of the Atlantic Multi-Decadal Oscillation. We anticipate a near-average probability for major hurricanes making landfall along the United States coastline and in the Caribbean. As is the case with all hurricane seasons, coastal residents are reminded that it only takes one hurricane making landfall to make it an active season for them. They should prepare the same for every season, regardless of how much activity is predicted.

(as of 4 August 2016)

By Philip J. Klotzbach[1]

In Memory of William M. Gray[2]

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

Anne Ju Manning, Colorado State University Media Representative, (970-491-7099) is available to answer various questions about this outlook.

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Dr. Bill Gray (1929-2016)

Dr. Gray passed away on April 16, 2016. He pioneered seasonal Atlantic hurricane prediction and conducted groundbreaking research in a wide variety of other topics including hurricane genesis, hurricane structure and cumulus convection. On a personal note, he was an amazing graduate advisor, mentor and friend. He will be greatly missed. I promised him when I saw him a few days before his death that I would give him at least 50 more years of seasonal forecasts. I will do my best to continue his legacy and produce seasonal Atlantic hurricane forecasts for as long as I can! A more in-depth eulogy is available here:

http://tropical.atmos.colostate.edu/Includes/Documents/gray_eulogy.pdf

ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2016

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 14 April 2016	Issue Date 1 June 2016	Issue Date 1 July 2016	Observed Activity Through July 2016	Forecast Activity After 31 July	**Total Seasonal Forecast**
Named Storms (NS) (12.0)	13	14	15	4	11	**15**
Named Storm Days (NSD) (60.1)	52	53	55	6.50	48.50	**55**
Hurricanes (H) (6.5)	6	6	6	1	5	**6**
Hurricane Days (HD) (21.3)	21	21	21	1	22	**23**
Major Hurricanes (MH) (2.0)	2	2	2	0	2	**2**
Major Hurricane Days (MHD) (3.9)	4	4	4	0	5	**5**
Accumulated Cyclone Energy (ACE) (92)	93	94	95	6	94	**100**
Net Tropical Cyclone Activity (NTC) (103%)	101	103	105	13	97	**110**

POST-31 JULY PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE LANDFALL ON EACH OF THE FOLLOWING UNITED STATES COASTAL AREAS:

1) Entire U.S. coastline - 51% (full-season average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 30% (full-season average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 29% (full-season average for last century is 30%)

POST-31 JULY PROBABILITIES FOR AT LEAST ONE MAJOR (CATEGORY 3-4-5) HURRICANE TRACKING INTO THE CARIBBEAN (10-20°N, 60-88°W)

1) 41% (full-season average for last century is 42%)

POST-31 JULY HURRICANE IMPACT PROBABILITIES FOR 2016 (NUMBERS IN PARENTHESES ARE LONG-PERIOD FULL SEASON AVERAGES)

State	Hurricane	Major Hurricane
Texas	32% (33%)	11% (12%)
Louisiana	29% (30%)	11% (12%)
Mississippi	10% (11%)	4% (4%)
Alabama	15% (16%)	3% (3%)
Florida	50% (51%)	20% (21%)
Georgia	11% (11%)	1% (1%)
South Carolina	17% (17%)	4% (4%)
North Carolina	28% (28%)	7% (8%)
Virginia	6% (6%)	1% (1%)
Maryland	1% (1%)	<1% (<1%)
Delaware	1% (1%)	<1% (<1%)
New Jersey	1% (1%)	<1% (<1%)
New York	7% (8%)	3% (3%)
Connecticut	7% (7%)	2% (2%)
Rhode Island	6% (6%)	3% (3%)
Massachusetts	7% (7%)	2% (2%)
New Hampshire	1% (1%)	<1% (<1%)
Maine	4% (4%)	<1% (<1%)

POST-31 JULY PROBABILITIES OF HURRICANES AND MAJOR HURRICANES TRACKING WITHIN 100 MILES OF EACH ISLAND OR LANDMASS FOR 2016 (NUMBERS IN PARENTHESES ARE LONG-PERIOD FULL SEASON AVERAGES)

Island/Landmass	Hurricane within 100 Miles	Major Hurricane within 100 Miles
The Bahamas	50% (51%)	29% (30%)
Cuba	51% (52%)	27% (28%)
Haiti	26% (27%)	13% (13%)
Jamaica	24% (25%)	11% (11%)
Mexico (East Coast)	56% (57%)	22% (23%)
Puerto Rico	28% (29%)	13% (13%)
Turks and Caicos	24% (24%)	9% (9%)
US Virgin Islands	29% (30%)	12% (12%)

Please also visit the Landfalling Probability Webpage at http://www.e-transit.org/hurricane for landfall probabilities for 11 U.S. coastal regions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine as well as probabilities for every island in the Caribbean.

ABSTRACT

Information obtained through July 2016 indicates that the 2016 Atlantic hurricane season will have activity near the median 1981-2010 season. There remains considerable uncertainty with this forecast which we outline in the following paragraphs.

We estimate that the remainder of 2016 will have about 5 hurricanes (average is 5.5), 11 named storms (average is 10.5), 48.5 named storm days (average is 58), 22 hurricane days (average is 21.3), 2 major (Category 3-4-5) hurricanes (average is 2.0) and 5 major hurricane days (average is 3.9). The probability of U.S. major hurricane landfall is estimated to be very near the long-period average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2016 to be near their long-term averages for the remainder of the season. The seasonal forecast for hurricane and major hurricanes days has been increased slightly from previous outlooks, in order to be in line with the ACE prediction from our early August statistical model.

There remains considerable uncertainty surrounding this outlook. Hurricane-enhancing conditions include cool neutral ENSO conditions, a slightly warmer-than-normal tropical Atlantic and relatively favorable upper-level wind conditions during July. However, the subtropical eastern Atlantic and far North Atlantic remain cooler than normal, and the tropical Atlantic atmosphere was also more stable than normal in July. These mixed signals and our early August statistical model output calling for a near-normal season are the primary reasons for the continued prediction of a near-average Atlantic hurricane season.

This forecast is based on an extended-range early August statistical prediction scheme developed on data from 1979-2011 and issued operationally since 2012. Analog predictors were also considered.

Starting today and issued every two weeks following (e.g., August 4, August 18, September 1, etc.), we will issue two-week forecasts for Atlantic TC activity during the peak of the Atlantic hurricane season from August-October. A late-season forecast for the Caribbean basin will be issued on Friday, September 30.

Coastal residents are reminded that it only takes one hurricane making landfall to make it an active season for them, and they need to prepare the same for every season, regardless of how much activity is predicted.

Why issue forecasts for seasonal hurricane activity?

We are frequently asked this question. Our answer is that it is possible to say something about the probability of the coming year's hurricane activity which is superior to climatology. The Atlantic basin has the largest year-to-year variability of any of the global tropical cyclone basins. People are curious to know how active the upcoming season is likely to be, particularly if you can show hindcast skill improvement over climatology for many past years.

Everyone should realize that it is impossible to precisely predict this season's hurricane activity in early August. There is, however, much curiosity as to how global ocean and atmosphere features are presently arranged as regards to the probability of an active or inactive hurricane season for the coming year. Our current early August statistical forecast methodology shows strong evidence over 37 past years that improvement over climatology can be attained. We utilize this newly-developed model when issuing this year's forecast. **We would never issue a seasonal hurricane forecast unless we had a statistical model constructed over a long hindcast period which showed significant skill over climatology.**

We issue these forecasts to satisfy the curiosity of the general public and to bring attention to the hurricane problem. There is a general interest in knowing what the odds are for an active or inactive season. One must remember that our forecasts are based on the premise that those global oceanic and atmospheric conditions which preceded comparatively active or inactive hurricane seasons in the past provide meaningful information about similar trends in future seasons. This is not always true for individual seasons. It is also important that the reader appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years. Moreover, these forecasts do not specifically predict where within the Atlantic basin these storms will strike. The probability of landfall for any one location along the coast is very low and reflects the fact that, in any one season, most U.S. coastal areas will not feel the effects of a hurricane no matter how active the individual season is.

Acknowledgment

We are grateful for support from Interstate Restoration, Ironshore Insurance and Macquarie Group that partially support the release of these predictions. We acknowledge a grant from the G. Unger Vetlesen Foundation for additional financial support. 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).

Colorado State University's seasonal hurricane forecasts have benefited greatly from a number of individuals that were former graduate students of William Gray. Among these former project members are Chris Landsea, John Knaff and Eric Blake. We also thank Professors Paul Mielke and Ken Berry of Colorado State University for statistical analysis and guidance 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, 50-10°W and sea level pressure from 0-50°N, 70-10°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 30-60 days.

Main Development Region (MDR) – An area in the tropical Atlantic where a majority of tropical cyclones that become major hurricanes form, which we define as 10-20°N, 20-60°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.

Saffir/Simpson Hurricane Wind Scale – A measurement scale ranging from 1 to 5 of hurricane wind 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 33rd 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. This year's August forecast is based on a statistical methodology developed on Atlantic hurricane seasons from 1979-2011 and has been utilized operationally since 2012. 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 3-4 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 should show significant hindcast skill before it is used in real-time forecasts.

1.1 2016 Atlantic Basin Activity through July

The 2016 Atlantic basin hurricane season has had approximately average TC activity, based on the ACE index, during June and July. Real-time global TC statistics are available here: http://tropical.atmos.colostate.edu/Realtime/.

Table 1 records observed Atlantic basin TC activity through 31 July, while tracks through 31 July are displayed in Figure 1. All TC activity calculations are based upon data available in the National Hurricane Center's b-decks.

Table 1: Observed 2016 Atlantic basin tropical cyclone activity through July 31. Dates listed are those where TCs had maximum sustained winds of at least 35 knots and are given in UTC time.

Highest Category	Name	Dates	Peak Sustained Winds (kts)/lowest SLP (mb)	NSD	HD	MHD	ACE	NTC
H-1	Alex	January 13 – 15	75 kt/981 mb	2.00	1.00		3.2	5.9
TS	Bonnie	May 28 – June 4	40 kt/1006 mb	2.00			1.0	2.4
TS	Colin	June 5 – 7	45 kt/1001 mb	1.75			1.2	2.3
TS	Danielle	June 20 – 21	40 kt/1007 mb	0.75			0.4	2.0
Totals	4			6.50	1.00		5.8	12.6

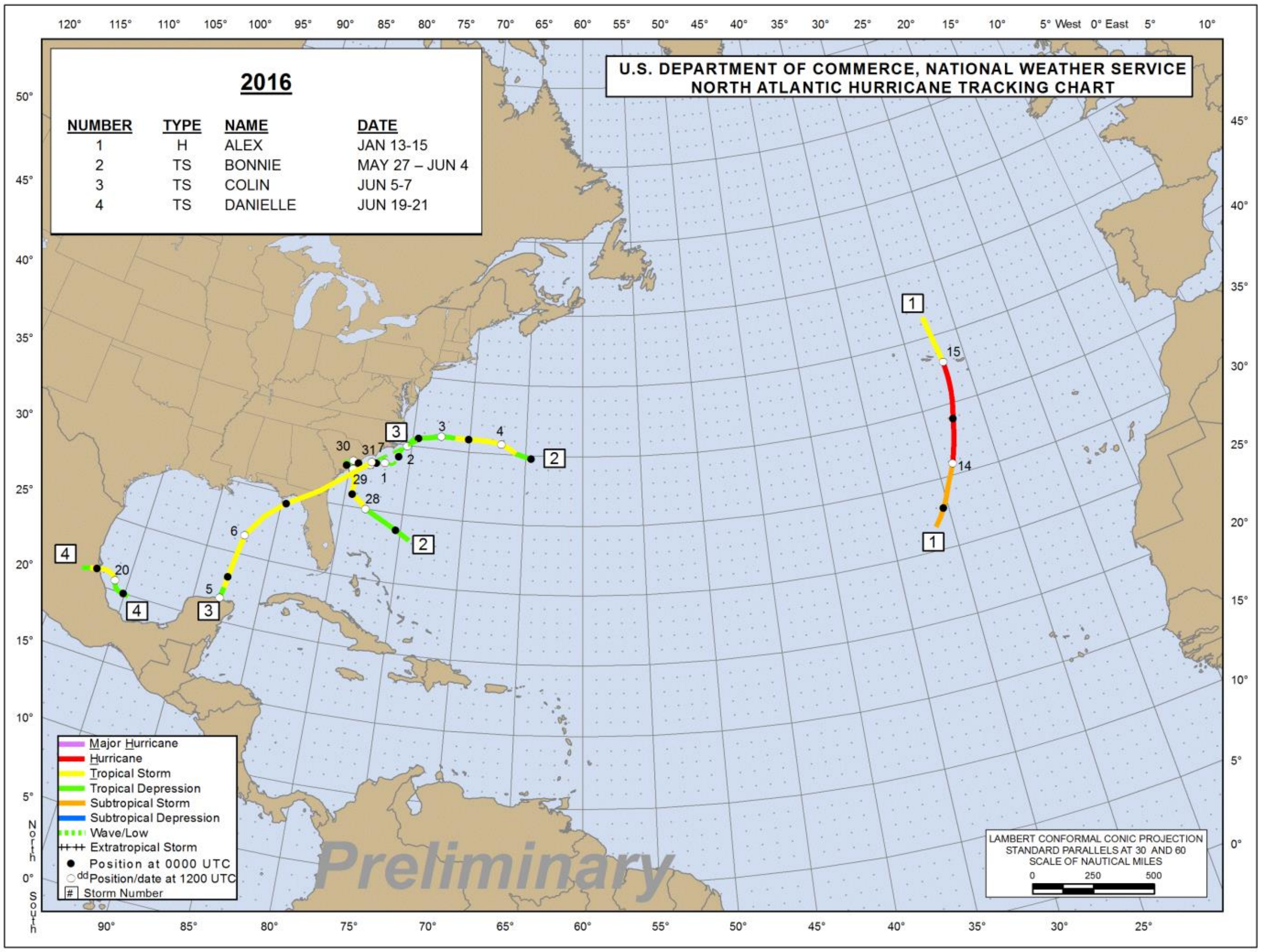

Figure 1: 2016 Atlantic basin hurricane tracks through July. Figure courtesy of National Hurricane Center (http://www.nhc.noaa.gov).

2 1 August Statistical Forecast Scheme

We developed a new 1 August statistical seasonal forecast scheme for the prediction of Accumulated Cyclone Energy (ACE) that was developed over the period from 1979-2011 and has been issued operationally since 2012. This model uses a total of three predictors, all of which are selected from the ERA-Interim Reanalysis dataset, which is available from 1979 to near-present. Real-time predictor estimates are done from the Climate Forecast System version 2 products, as ERA-Interim Reanalysis products are not available in real time. The major components of the forecast scheme are discussed in the next few paragraphs.

The pool of three predictors for the early August statistical forecast scheme is given and defined in Table 2. The location of each of these predictors is shown in Figure 2. Skillful forecasts can be issued for post-31 July ACE based upon hindcast results over the period from 1979-2011 as well as real-time forecasts in 2012, 2014 and 2015. Like all of our other forecasts, the model did not anticipate the below-average 2013 Atlantic hurricane season. When these three predictors are combined, they correlate at 0.86 with observed ACE using hindcasts/forecasts over the period from 1979-2015 (Figure 3).

Table 2: Listing of 1 August 2016 predictors for this year's hurricane activity. A plus (+) means that positive deviations of the parameter indicate increased hurricane activity this year, and a minus (-) means that positive deviations of the parameter indicate decreased hurricane activity this year. None of the three predictors deviate significantly from their climatological values, giving increased confidence to the near-average forecast.

Predictor	Values for 2016 Forecast	Effect on 2016 Hurricane Season
1) July Surface U (10-17.5°N, 60-85°W) (+)	+0.3 SD	Slightly Enhance
2) July Surface Temperature (20-40°N, 15-35°W) (+)	-0.2 SD	Slightly Suppress
3) July 200 mb U (5-15°N, 0-40°E) (-)	+0.8 SD	Slightly Suppress

Post-31 July Seasonal Forecast Predictors

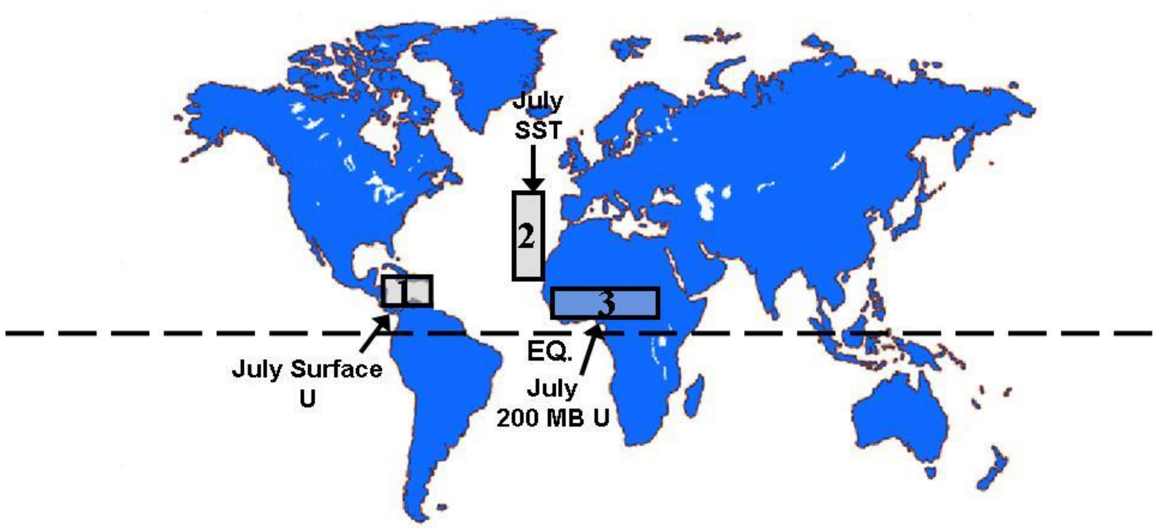

Figure 2: Location of predictors for the post-31 July forecast for the 2016 hurricane season from the new statistical model.

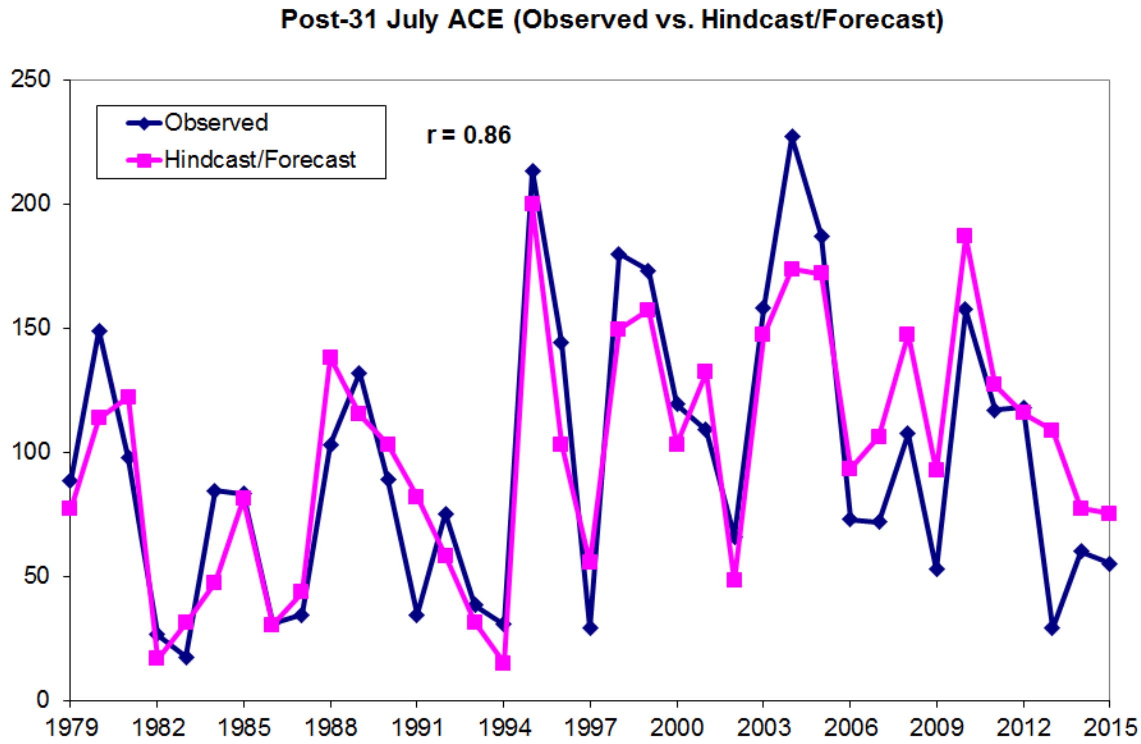

Figure 3: Observed versus hindcast values of post-31 July ACE for 1979-2015 using our current statistical scheme.

Table 3 shows our statistical forecast for the 2016 hurricane season from the new statistical model and the comparison of this forecast with the 1981-2010 median. Our statistical forecast is calling for a near-average hurricane season.

Table 3: Post-31 July statistical forecast for 2016 from the statistical model.

Predictands and Climatology (1981-2010 Post-31 July Median)	Statistical Forecast
Named Storms (NS) – 10.5	10.5
Named Storm Days (NSD) – 58.0	51.0
Hurricanes (H) – 5.5	5.9
Hurricane Days (HD) – 21.3	22.6
Major Hurricanes (MH) – 2.0	2.4
Major Hurricane Days (MHD) – 3.8	5.5
Accumulated Cyclone Energy Index (ACE) – 86	94
Net Tropical Cyclone Activity (NTC) – 95	103

Table 4 displays our early August hindcasts for 1979-2011 along with the real-time forecasts in 2012-2015 using the current statistical scheme. Our early August model has correctly predicted above- or below-average post-31 July ACE in 32 out of 37 years

(86%). These hindcasts have had a smaller error than climatology in 25 out of 37 years (68%). Our average hindcast errors have been 23 NTC units, compared with 46 NTC units had we used only climatology.

Table 4: Observed versus hindcast post-31 July ACE for 1979-2015 using the current statistical scheme. Average errors for hindcast ACE and climatological ACE predictions are given without respect to sign. Red bold-faced years in the "Hindcast ACE" column are years that we did not go the right way, while red bold-faced years in the "Hindcast improvement over Climatology" column are years that we did not beat climatology.

Year	Observed ACE	Hindcast ACE	Observed minus Hindcast	Observed minus Climatology	Hindcast improvement over Climatology
1979	88	**77**	12	2	**-9**
1980	149	113	35	63	27
1981	98	122	-24	12	**-13**
1982	27	17	10	-59	50
1983	17	31	-14	-69	55
1984	84	47	37	-2	**-35**
1985	83	81	2	-3	1
1986	31	30	0	-55	55
1987	34	43	-9	-52	43
1988	103	138	-35	17	**-18**
1989	132	115	17	46	29
1990	89	103	-14	3	**-11**
1991	34	82	-48	-52	4
1992	75	58	17	-11	**-6**
1993	38	31	7	-48	41
1994	30	15	16	-56	40
1995	213	200	14	127	114
1996	144	103	41	58	17
1997	29	55	-26	-57	31
1998	180	149	31	94	63
1999	173	157	16	87	71
2000	119	103	16	33	17
2001	109	132	-23	23	**-1**
2002	66	48	18	-20	2
2003	158	147	11	72	61
2004	227	174	53	141	88
2005	187	172	15	101	86
2006	73	**93**	-20	-13	**-7**
2007	72	**106**	-34	-14	**-20**
2008	107	147	-40	21	**-18**
2009	53	**92**	-40	-33	**-6**
2010	157	187	-29	71	42
2011	117	127	-10	31	21
2012	118	116	2	32	30
2013	29	**109**	-80	-57	**-23**
2014	60	77	-17	-26	9
2015	55	75	-20	-31	11
Average	**96**	**99**	**|23|**	**|46|**	**+23***

* This shows that we obtain a net (23/46) or 50 percent improvement over the year-to-year variance from climatology.

2.2 Physical Associations among Predictors Listed in Table 2

The locations and brief descriptions of the three predictors for our current August statistical forecast are now discussed. It should be noted that all forecast parameters correlate significantly with physical features during August through October that are known to be favorable for elevated levels of TC activity. For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of SST, sea level pressure (SLP), 850 mb (~1.5 km altitude) zonal wind (U), and 200 mb (~12 km altitude) zonal wind (U), respectively.

Predictor 1. July Surface U in the Caribbean (+)

(10-17.5°N, 60-85°W)

Low-level trade wind flow has been utilized as a predictor in seasonal forecasting systems for the Atlantic basin (Lea and Saunders 2004). When the trades are weaker-than-normal, SSTs across the tropical Atlantic tend to be elevated, and consequently a larger-than-normal Atlantic Warm Pool (AWP) is typically observed (Wang and Lee 2007) (Figure 4). A larger AWP also correlates with reduced vertical shear across the tropical Atlantic. Weaker trade winds are typically associated with higher pressure in the tropical eastern Pacific (a La Niña signal) and lower pressure in the Caribbean and tropical Atlantic. Both of these conditions generally occur when active hurricane seasons are observed. Predictor 1 also has a strong negative correlation with August-October-averaged 200-850-mb zonal shear.

Predictor 2. July Surface Temperature in the Northeastern Subtropical Atlantic (+)

(20°-40°N, 15-35°W)

A similar predictor was utilized in earlier August seasonal forecast models (Klotzbach 2007, Klotzbach 2011). Anomalously warm SSTs in the subtropical North Atlantic are associated with a positive phase of the Atlantic Meridional Mode (AMM), a northward-shifted Intertropical Convergence Zone, and consequently, reduced trade wind strength (Kossin and Vimont 2007). Weaker trade winds are associated with less surface evaporative cooling and less mixing and upwelling. This results in warmer tropical Atlantic SSTs during the August-October period (Figure 5).

Predictor 3. July 200 mb U over Northern Tropical Africa (-)

(5-15°N, 0-40°E)

Anomalous easterly flow at upper levels over northern tropical Africa provides an environment that is more favorable for easterly wave development into TCs. This anomalous easterly flow tends to persist through August-October, which reduces shear over the Main Development Region (MDR). This predictor also correlates with SLP and SST anomalies over the tropical eastern Pacific that are typically associated with cool ENSO conditions (Figure 6).

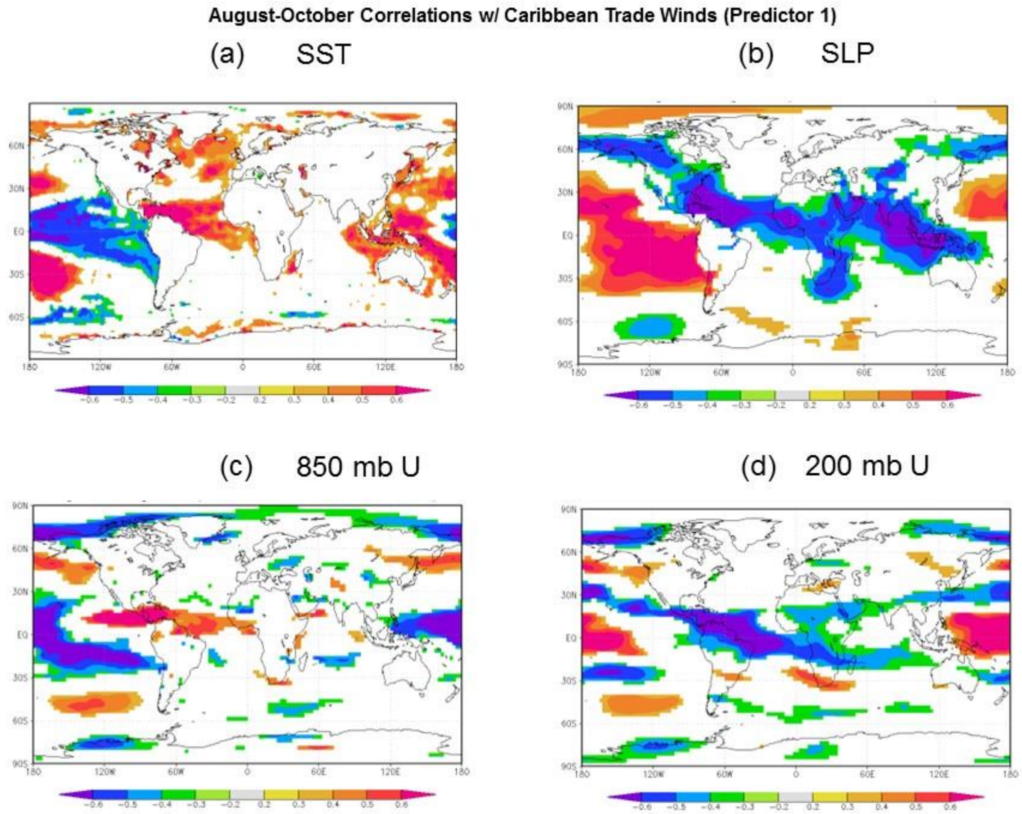

Figure 4: Linear correlations between July Surface U in the Caribbean (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d) over the period from 1979-2011.

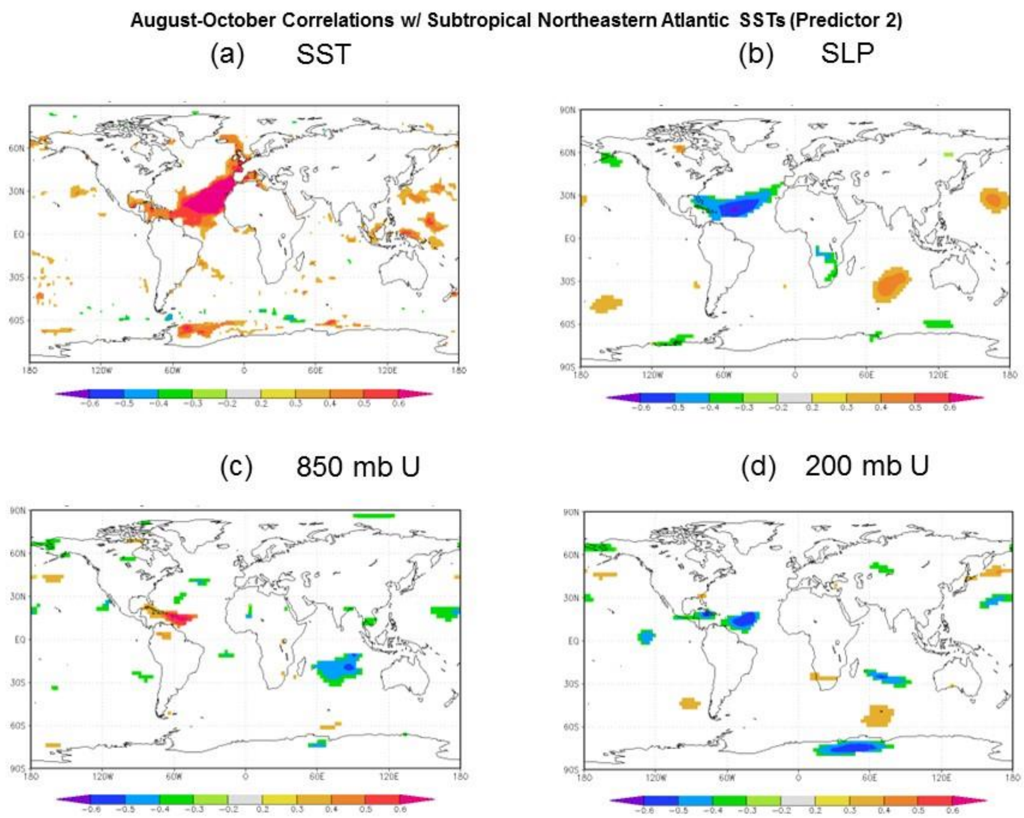

Figure 5: Linear correlations between July Surface Temperature in the Subtropical Northeastern Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d) over the period from 1979-2011.

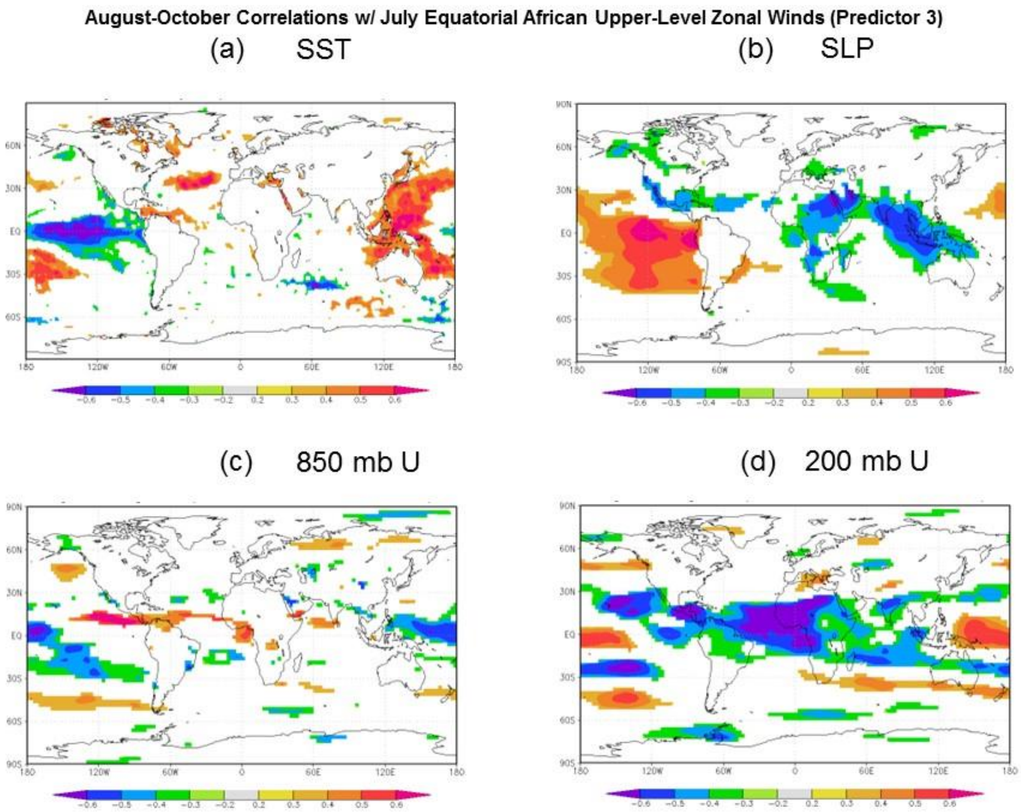

Figure 6: Linear correlations between <u>July 200 MB Zonal Wind</u> over tropical north Africa <u>(Predictor 3)</u> and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 925 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d) over the period from 1979-2011. The color scale has been reversed so that the correlations match up with those in Figures 4 and 5.

3 Forecast Uncertainty

One of the questions that we are asked regarding our seasonal hurricane predictions is the degree of uncertainty that is involved. Obviously, our predictions are our best estimate, but there is with all forecasts an uncertainty as to how well they will verify.

Table 5 provides our post-31 July forecast, with error bars (based on one standard deviation of absolute errors) as calculated from hindcasts/forecasts of the Klotzbach (2007) scheme over the 1990-2009 period, using equations developed over the 1950-1989 period. We typically expect to see 2/3 of our forecasts verify within one standard deviation of observed values, with 95% of forecasts verifying within two standard deviations of observed values.

Table 5: Model hindcast error and our post-31 July 2016 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

Parameter	Hindcast Error (SD)	Post-31 July 2016 Forecast	Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range)
Named Storms (NS)	2.3	11	8.7 - 13.3
Named Storm Days (NSD)	17.4	48.50	31.1 – 65.9
Hurricanes (H)	1.6	5	3.4 – 6.6
Hurricane Days (HD)	8.6	22	13.4 – 30.6
Major Hurricanes (MH)	0.9	2	1.1 – 2.9
Major Hurricane Days (MHD)	3.5	5	1.5 – 8.5
Accumulated Cyclone Energy (ACE)	36	94	58 – 130
Net Tropical Cyclone (NTC) Activity	34	97	63 - 131

4 Analog-Based Predictors for 2016 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are substantially similar to 2016. These years also provide useful clues as to likely trends in activity that the 2016 hurricane season may bring. For this early August forecast we determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current June-July 2016 conditions as well as conditions that we anticipate to be present during the peak months of the Atlantic hurricane season from August-October. Table 6 lists the best analog selections from our historical database.

We select prior hurricane seasons since 1950 which have similar atmospheric-oceanic conditions to those currently being experienced. We searched for years that had cool ENSO neutral to weak La Niña conditions along with Atlantic SST configurations that were similar to what we are currently experiencing.

There were six hurricane seasons with characteristics most similar to what we observed in June-July 2016. The best analog years that we could find for the 2016 hurricane season were 1958, 1959, 1966, 1978, 1992 and 1998. We anticipate that 2016 seasonal hurricane activity will have activity close to the average of these six analog years. We believe that the remainder of 2016 will have near-average activity in the Atlantic basin.

Table 6: Best analog years for 2016 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	MH	MHD	ACE	NTC
1958	12	58.75	7	26.75	3	6.25	110	121
1959	14	51.25	7	16.25	2	3.25	77	98
1966	11	64.00	7	41.75	3	8.75	145	140
1978	12	43.50	5	13.50	2	3.50	63	85
1992	7	40.25	4	16.00	1	3.50	76	67
1998	14	88.00	10	48.50	3	9.50	182	169
Mean (Full Season)	**11.7**	**57.6**	**6.7**	**27.1**	**2.3**	**5.8**	**109**	**113**
2016 Forecast (Full Season)	**15**	**55**	**6**	**23**	**2**	**5**	**100**	**110**
1981-2010 Median (Full Season)	**12.0**	**60.1**	**6.5**	**21.3**	**2.0**	**3.9**	**92**	**103**

5 ENSO

Cool neutral ENSO conditions currently exist across the tropical Pacific. Table 7 displays July and May SST anomalies for several Nino regions. The eastern and central tropical Pacific have continued to cool over the past few weeks.

Table 7: May and July 2015 SST anomalies for Nino 1+2, Nino 3, Nino 3.4, and Nino 4, respectively. July-May SST anomaly differences are also provided.

Region	May SST Anomaly (°C)	July SST Anomaly (°C)	July minus May SST Change (°C)
Nino 1+2	+0.3	+0.1	-0.2
Nino 3	+0.0	-0.5	-0.5
Nino 3.4	+0.3	-0.5	-0.8
Nino 4	+0.6	+0.3	-0.3

There remains some uncertainty as to whether the tropical Pacific will remain cool neutral or transition to La Niña conditions for the peak of the Atlantic hurricane season from August-October. While SSTs have cooled over the past few weeks, upper-ocean heat content anomalies over the tropical eastern and central Pacific have risen somewhat since May.

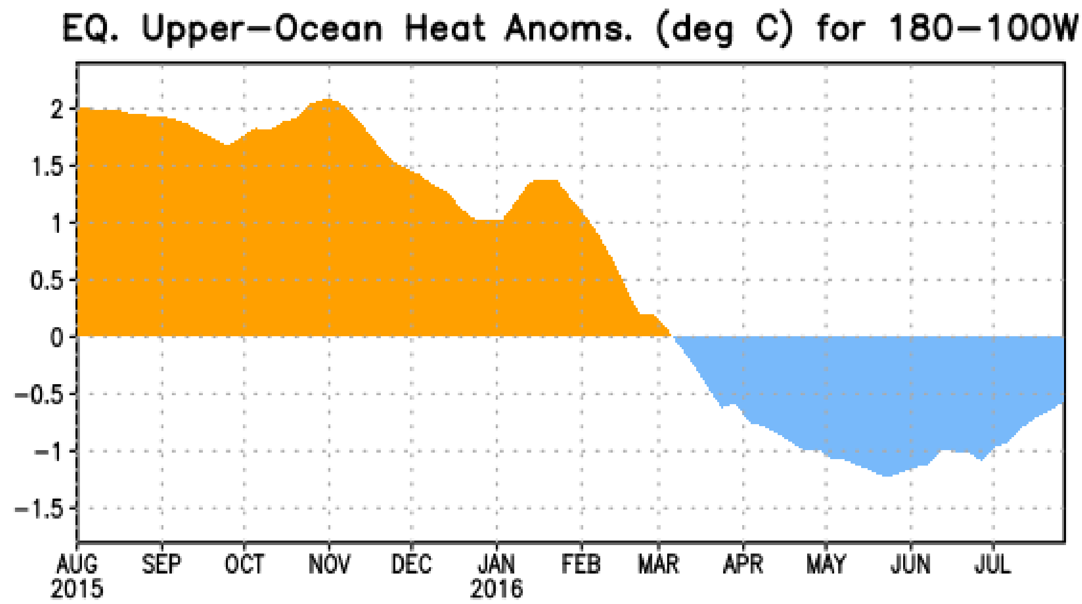

Figure 7: Upper-ocean (0-300 meters depth) heat content anomalies in the eastern and central Pacific since August 2015. Upper ocean heat content decreased rapidly from February to mid-May and have increased since that time.

One of the reasons why the transition away from El Niño has been relatively slow may be due to the absence of strong trade winds across the tropical Pacific. Stronger-than-normal trades favor upwelling and cooling in the eastern and central equatorial Pacific. As Figure 8 shows, low-level wind flow has been near-average across the tropical Pacific for the past several months.

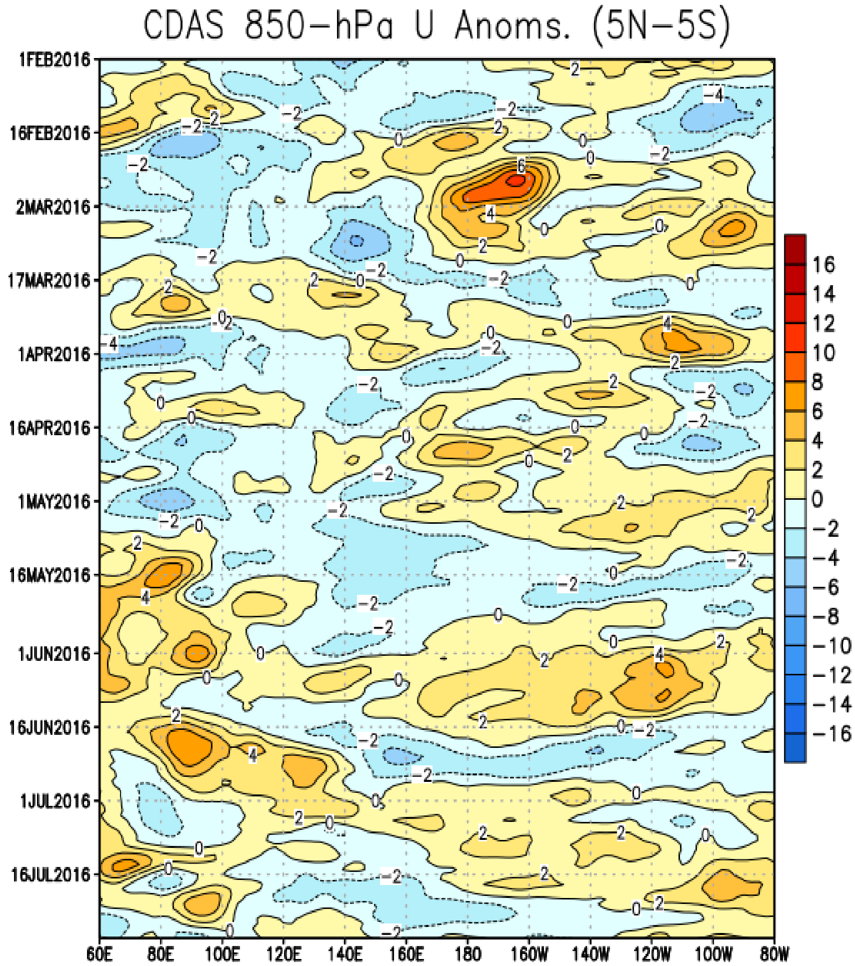

Figure 8: Anomalous 850-mb winds across the tropical Indian and Pacific Oceans from 60°E-80°W. Trade winds have generally been at near-average levels over the past few months.

There has also been a lack of significant oceanic Kelvin wave activity over the past few months (Figure 9). After several strong oceanic Kelvin waves this spring, a slow cooling has been observed across the tropical Pacific basin. Oceanic Kelvin wave propagation can trigger more rapid temperature fluctuations.

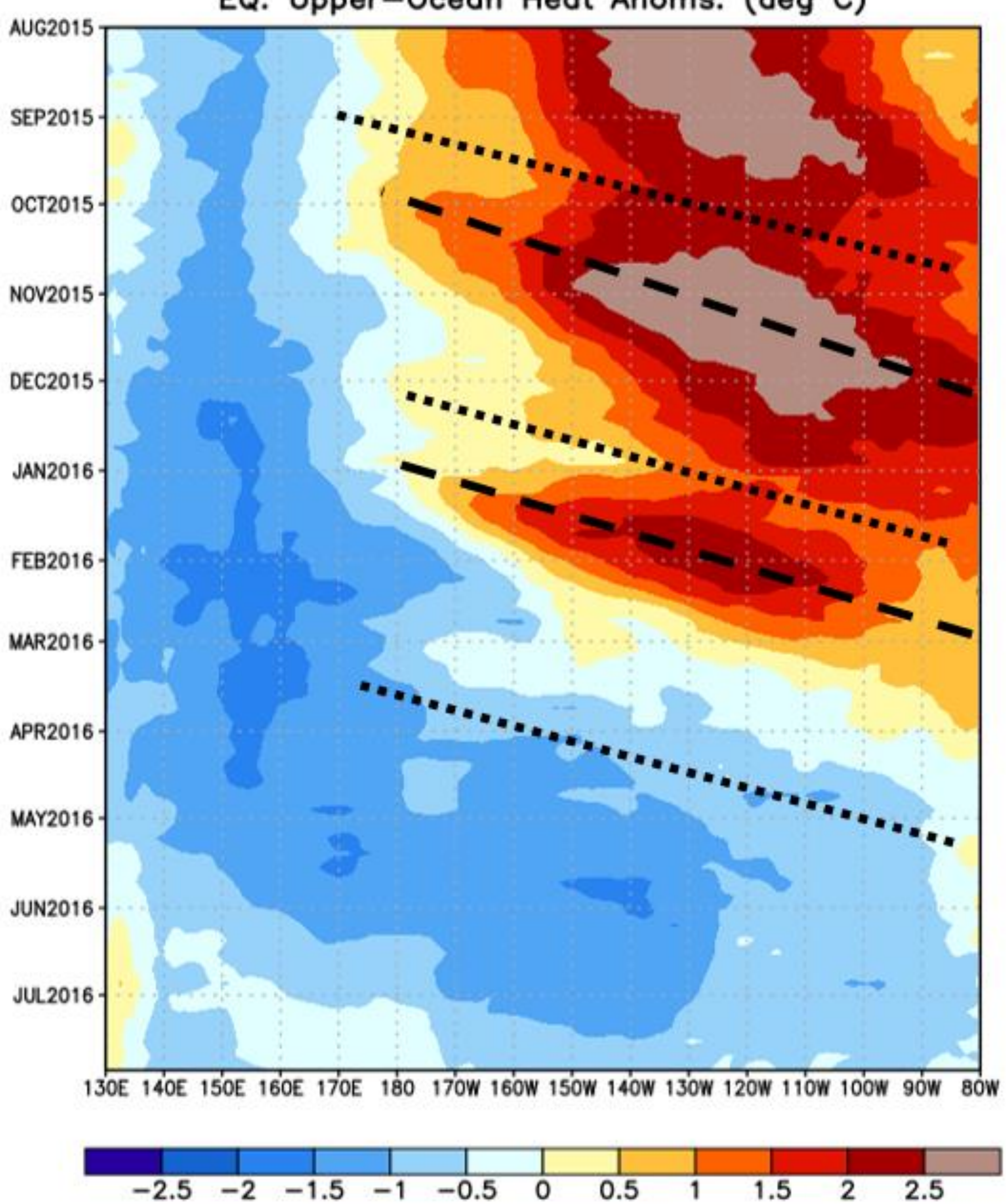

Figure 9: Upper-ocean heat content anomalies across the tropical Pacific. Dashed lines indicate downwelling (warming) Kelvin waves, while dotted lines indicate upwelling (cooling) Kelvin waves. Oceanic Kelvin wave activity appears to have been fairly limited over the past few months.

The European Centre for Medium-Range Weather Forecasts (ECMWF) typically shows the best prediction skill of the various ENSO models. The correlation skill between a 1 July forecast from the ECMWF model and the observed September Nino 3.4 anomaly is 0.89, based on hindcasts/forecasts from 1982-2010, explaining approximately 79% of the variance in Nino 3.4 SST. For reference, the correlation skill of a 1 May forecast from the ECMWF model was 0.82, indicating that approximately 15% additional variance can be explained by shortening the lead time of the forecast from 1 May to 1 July. The ECMWF model has recently been upgraded to system 4, indicating that improved ENSO skill may be possible. The ensemble average of the ECMWF model is calling for cool neutral ENSO conditions during the peak of the Atlantic hurricane season. In addition, only 1 of the 50 ECMWF ensemble members is predicting La Niña conditions during September. Climatologically, September is the most active month of the Atlantic hurricane season.

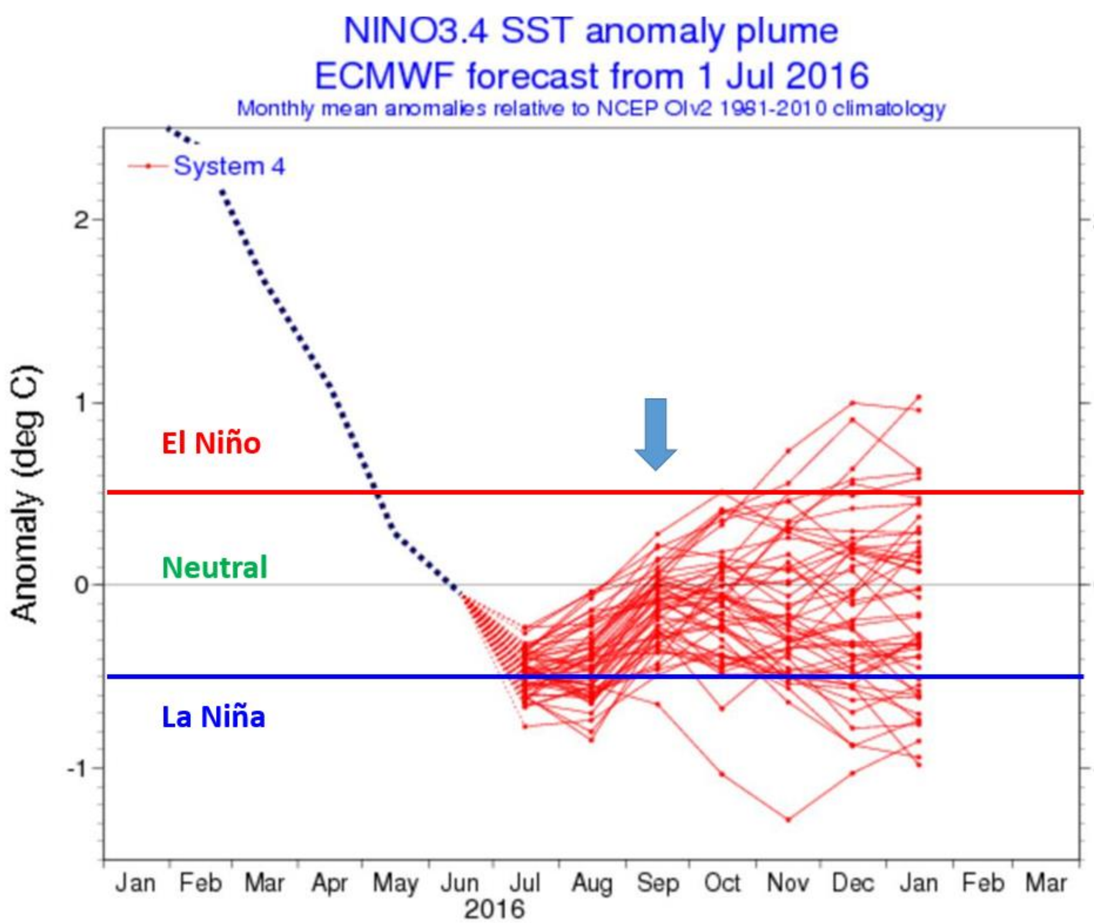

Figure 10: ECMWF ensemble model forecast for the Nino 3.4 region. The ECMWF ensemble average calls for cool neutral ENSO conditions during the peak months of the Atlantic hurricane season from August-October.

Most of the ensemble members of NOAA's Climate Forecast System (CFS) model are calling for cool neutral to weak La Niña conditions for August-October (Figure 11). Based on our assessment of both current conditions as well as forecast model output, our best estimate is that we will likely have cool neutral to weak La Niña conditions for August-October. This is somewhat a question of semantics; however, as whether the Nino 3.4 region is -0.4°C (defined as cool neutral) or -0.6°C (defined to be weak La Niña) makes relatively little difference in terms of its impacts on the Atlantic hurricane season.

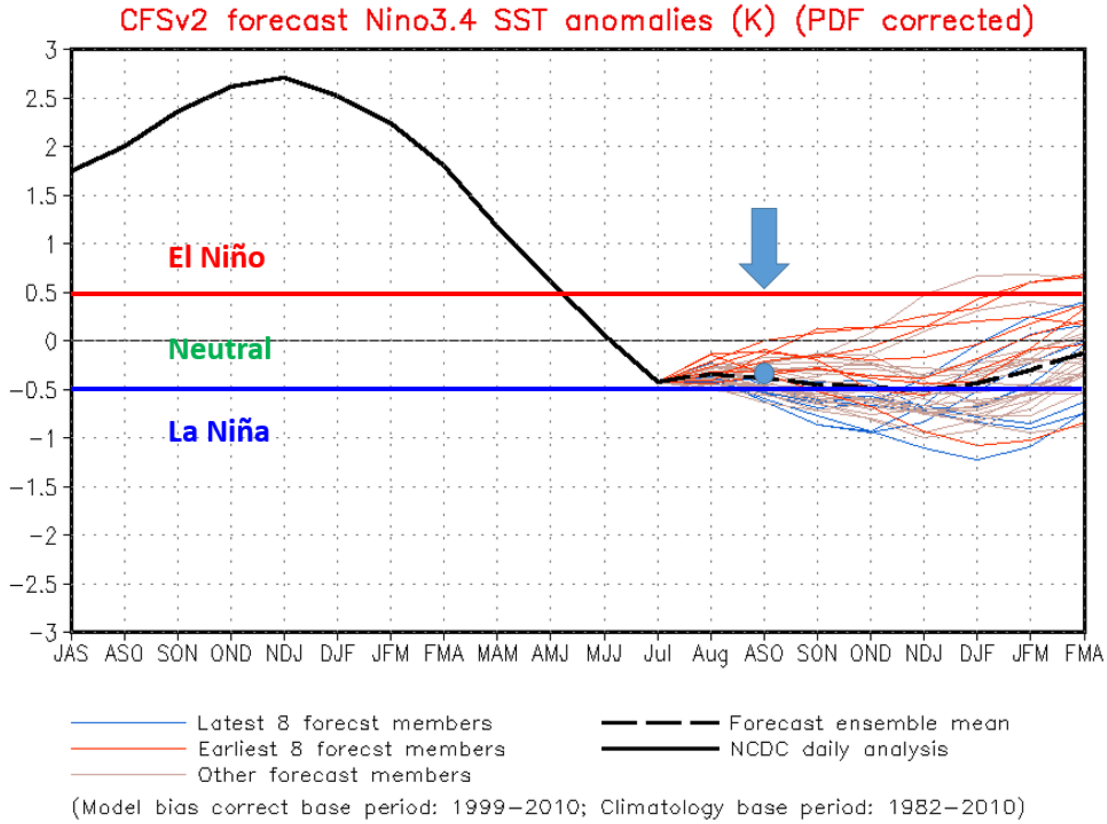

Figure 11: CFS ensemble model forecast for the Nino 3.4 region. The CFS ensemble average calls for cool neutral ENSO conditions during the peak months of the Atlantic hurricane season from August-October.

6 Current Atlantic Basin Conditions

The most challenging aspect of this year's Atlantic basin seasonal hurricane forecast remain the current configuration of atmospheric and oceanic patterns across the Atlantic basin. Figure 12 displays SST anomalies observed across the North Atlantic in July. The western Atlantic is very warm right now, while the eastern tropical Atlantic is slightly warmer than normal. However, the far North Atlantic and subtropical eastern Atlantic are somewhat cooler than normal. The current SST anomaly pattern somewhat resembles a negative Atlantic Multi-decadal Oscillation (AMO) pattern; however, the tropical Atlantic is typically also cooler than normal in a canonical negative AMO phase. The July 2016 SST pattern does not strongly resemble the July SST pattern typically associated with active Atlantic hurricane seasons (Figure 13).

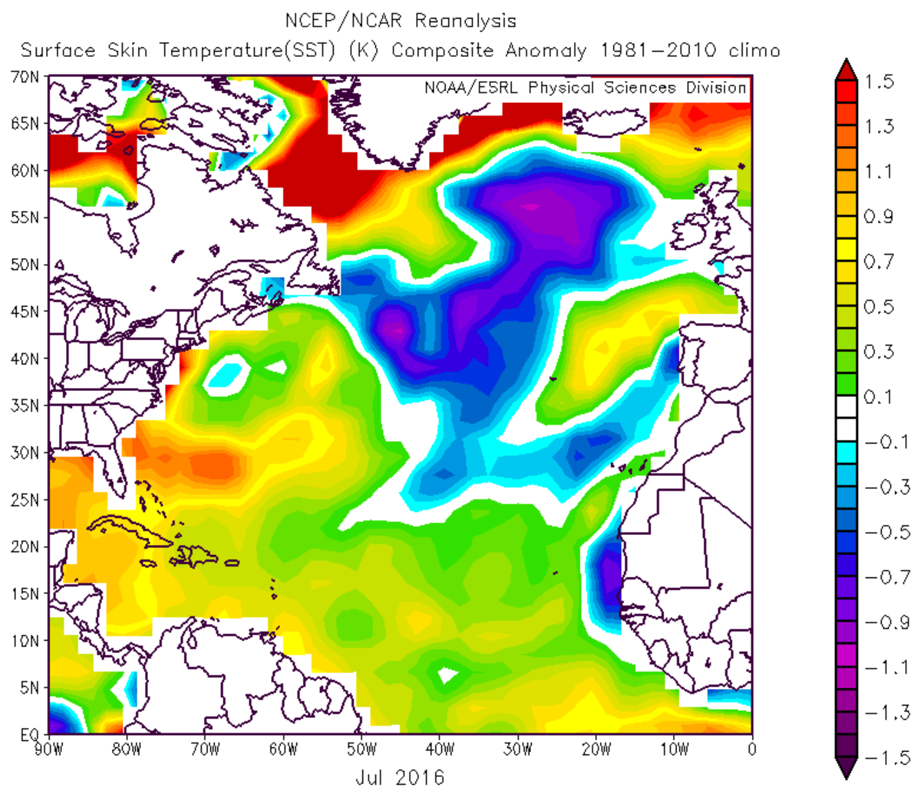

Figure 12: July 2016 SST anomalies.

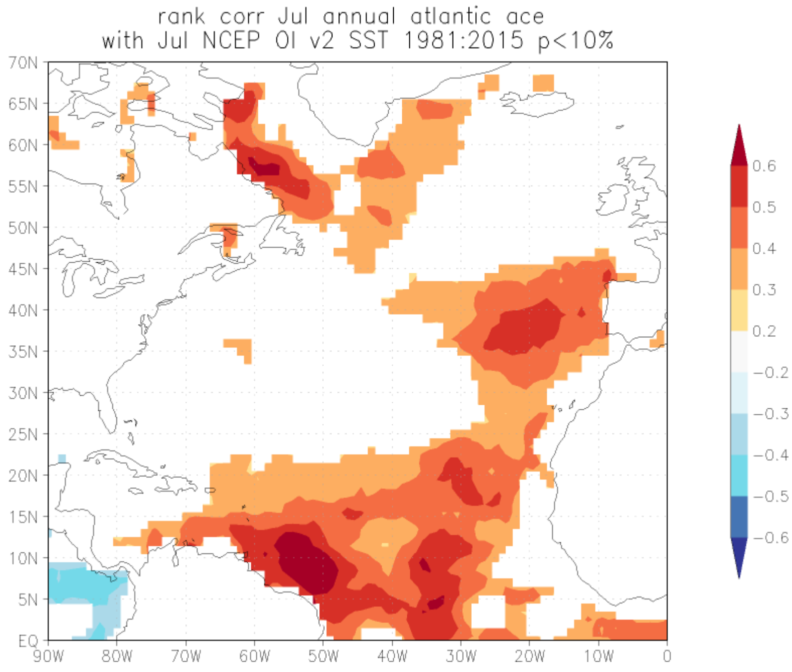

Figure 13: Correlation map between July SSTs and seasonal Atlantic ACE based on data over the period from 1982-2015.

Sea level pressure anomalies over the past month have been relatively low across the Main Development Region, implying that the Tropical Upper Tropospheric Trough (TUTT) is not particularly strong (Figure 13). A strong TUTT typically relates to increased vertical wind shear across the tropical Atlantic and Caribbean (Knaff 1997).

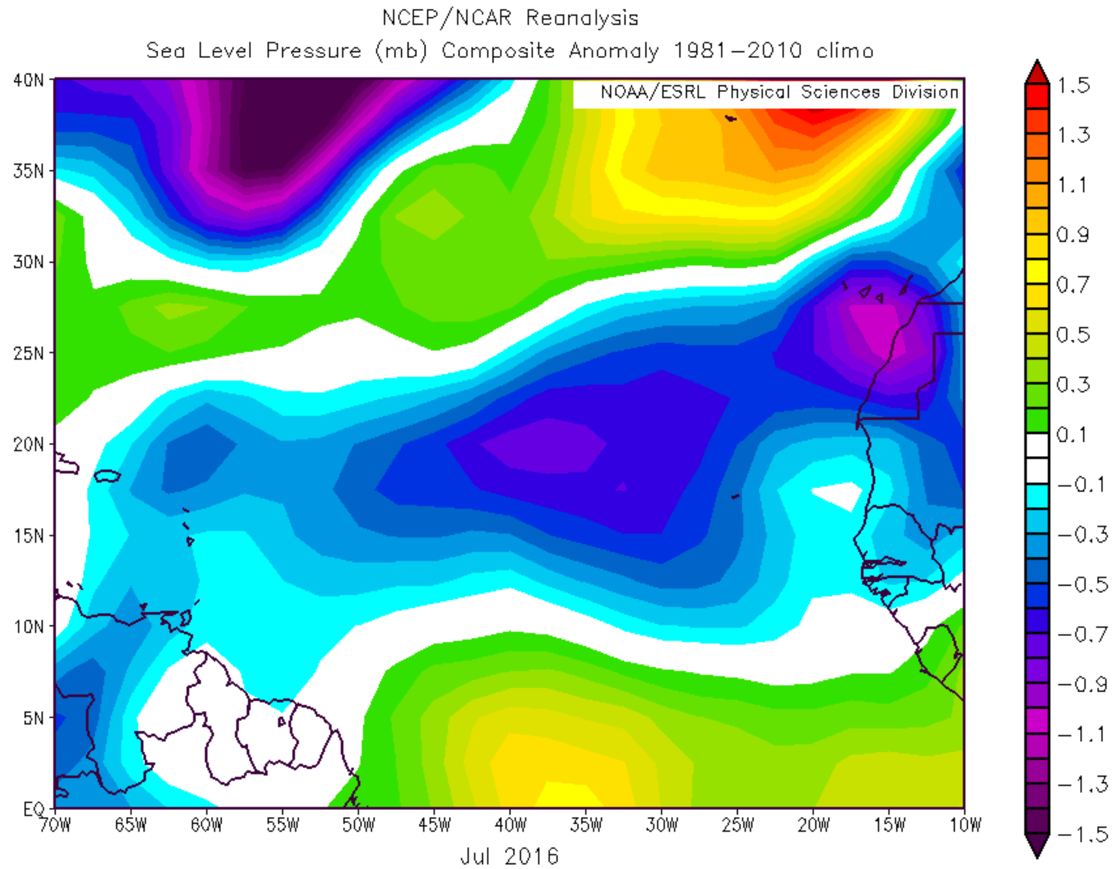

Figure 13: July 2016 Atlantic SLP anomaly. Sea level pressure anomalies were slightly below average across portions of the MDR.

Vertical wind shear has been significantly reduced over the past few weeks compared with the long-term average. The 200-850 mb zonal wind shear has been below average across the tropical Atlantic, with slightly above-average shear prevailing across the western Caribbean (Figure 14). Zonal vertical wind shear averaged across the Main Development Region (10-20°N, 60-20°W) in July was the 3rd weakest on record in the satellite era (since 1966). However, it should be noted while there is a moderate negative correlation between July MDR shear and Atlantic ACE (Figure 15), the two Julys with weaker shear across the MDR than 2016 ended up with near-normal ACE levels (1975 and 1988).

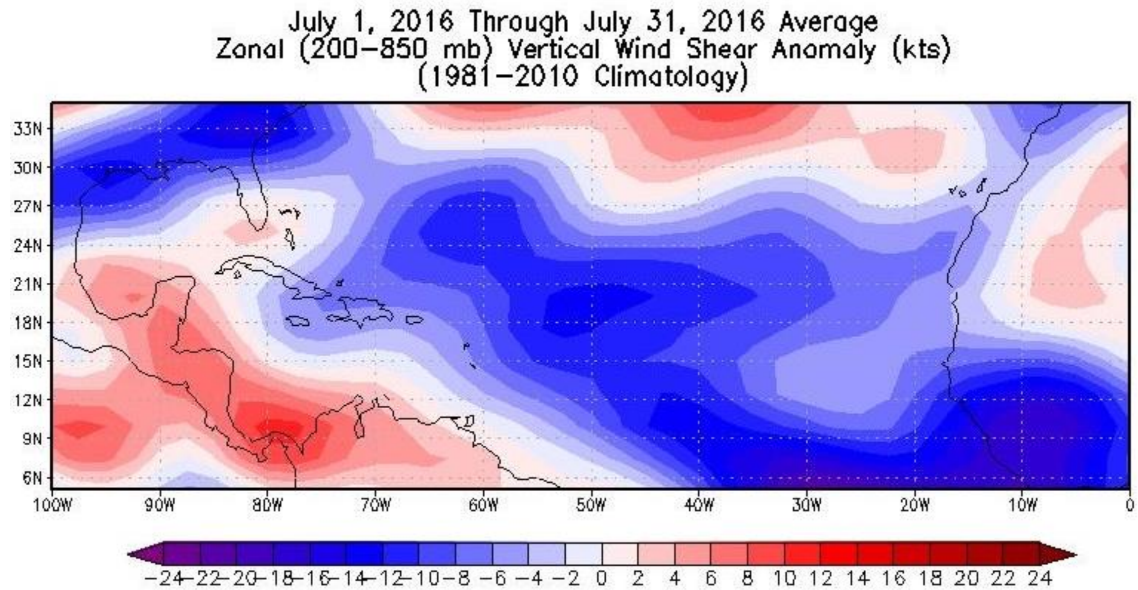

Figure 14: July 2016 averaged 200-850-mb zonal wind anomalies across the tropical Atlantic

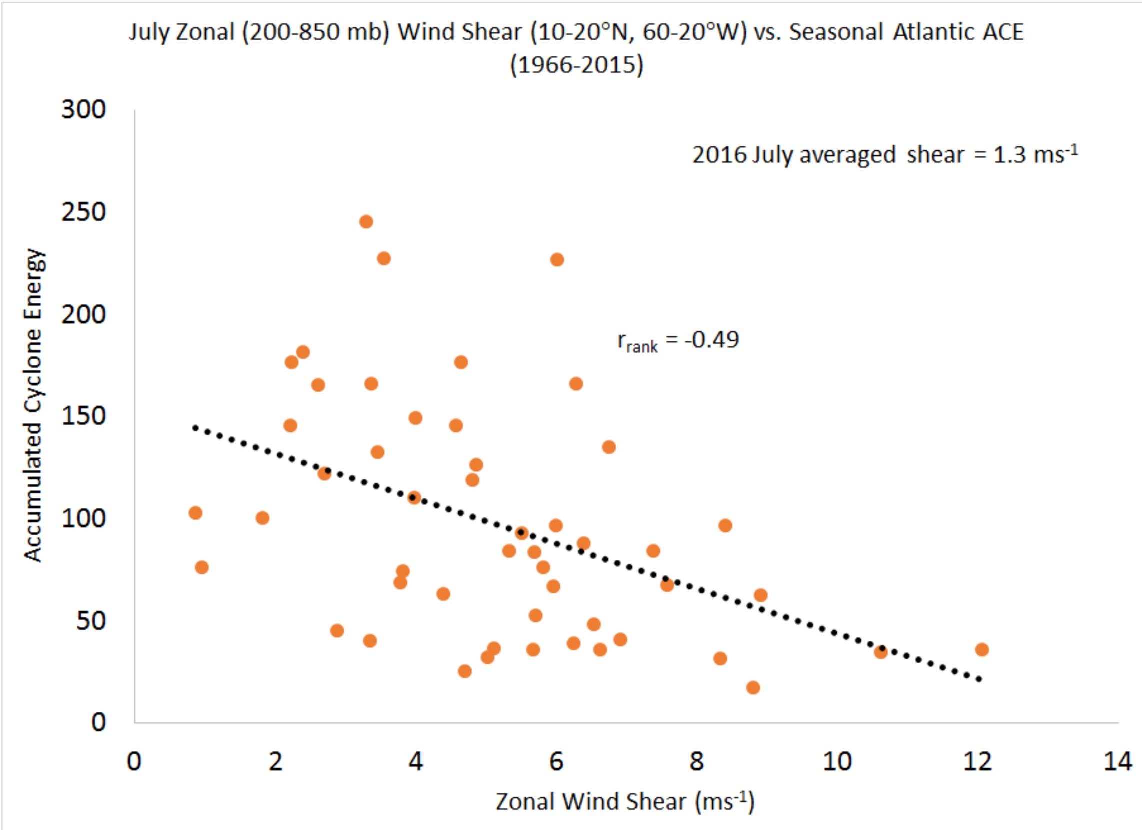

Figure 15: Correlation between zonal vertical wind shear across the MDR and seasonal Atlantic ACE. In general, years with weaker vertical wind shear in July tend to be more active.

As was the case the past couple of years, the tropical Atlantic has been drier than normal in July. The dryness across the Caribbean was quite pronounced this year (Figure 16).

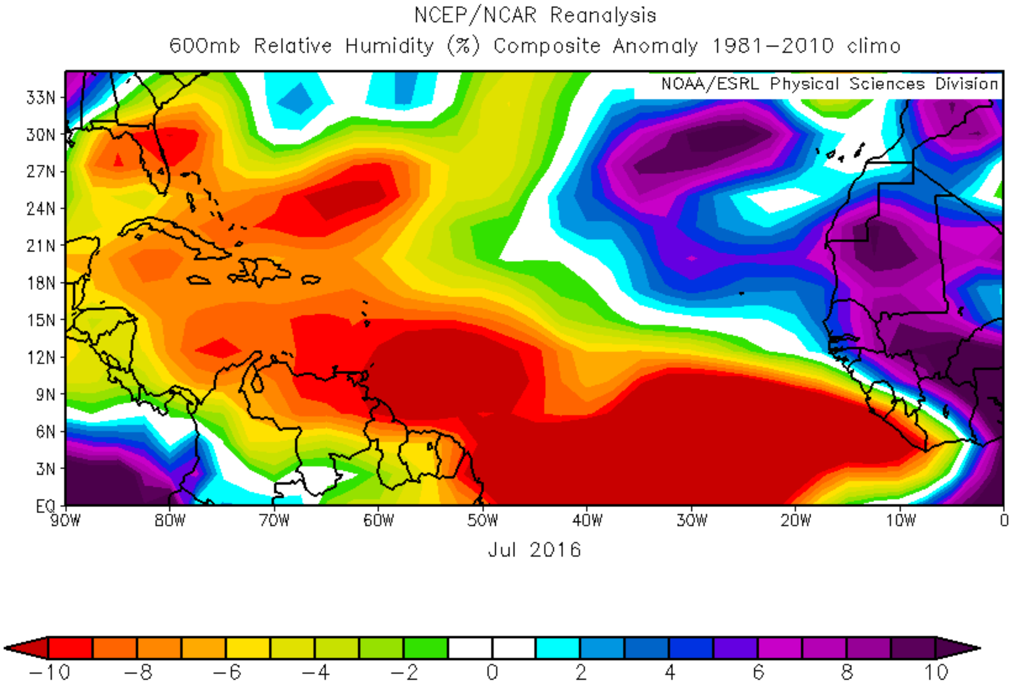

Figure 16: July 2016 600-mb relative humidity anomalies across the tropical Atlantic. Very dry conditions have been observed across the Caribbean.

The Cooperative Research Institute for the Atmosphere (CIRA) monitors real-time conditions for genesis in the tropical Atlantic, and according to their analysis, vertical instability is significantly below normal this year (Figure 17). Positive deviations from the curve displayed below indicate a more unstable atmosphere than normal. In general, the atmosphere has been much more stable than normal since the start of this year's hurricane season.

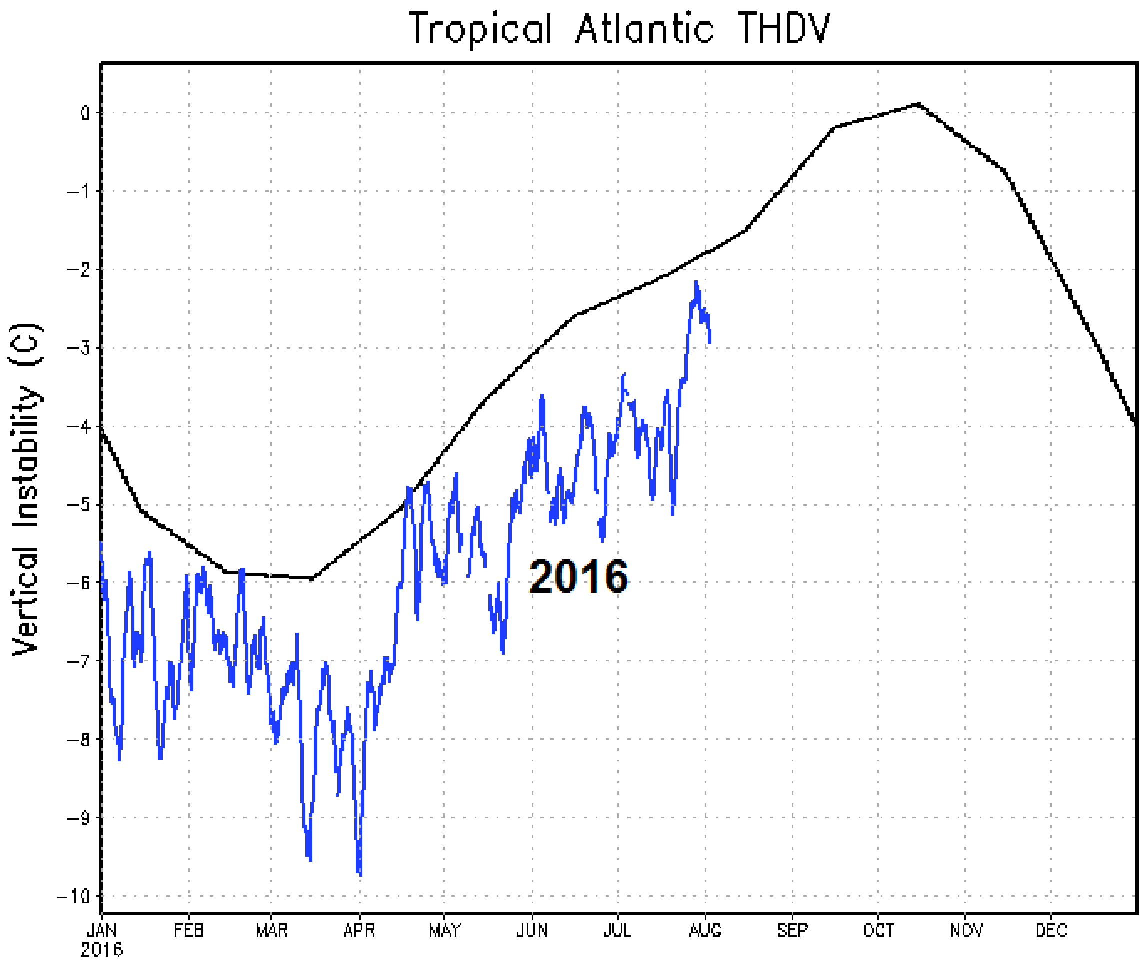

Figure 16: Vertical instability across the tropical Atlantic since January 2016 (blue line). The average season is represented by the black line.

7 West Africa Conditions

Enhanced rainfall in the Sahel region of West Africa during July has been associated with active hurricane seasons (Landsea and Gray 1992). Figure 17 displays rainfall estimates over Africa from July 2-31. In general, rainfall in the western Sahel looks to have been somewhat greater than normal, which would tend to favor a more active season.

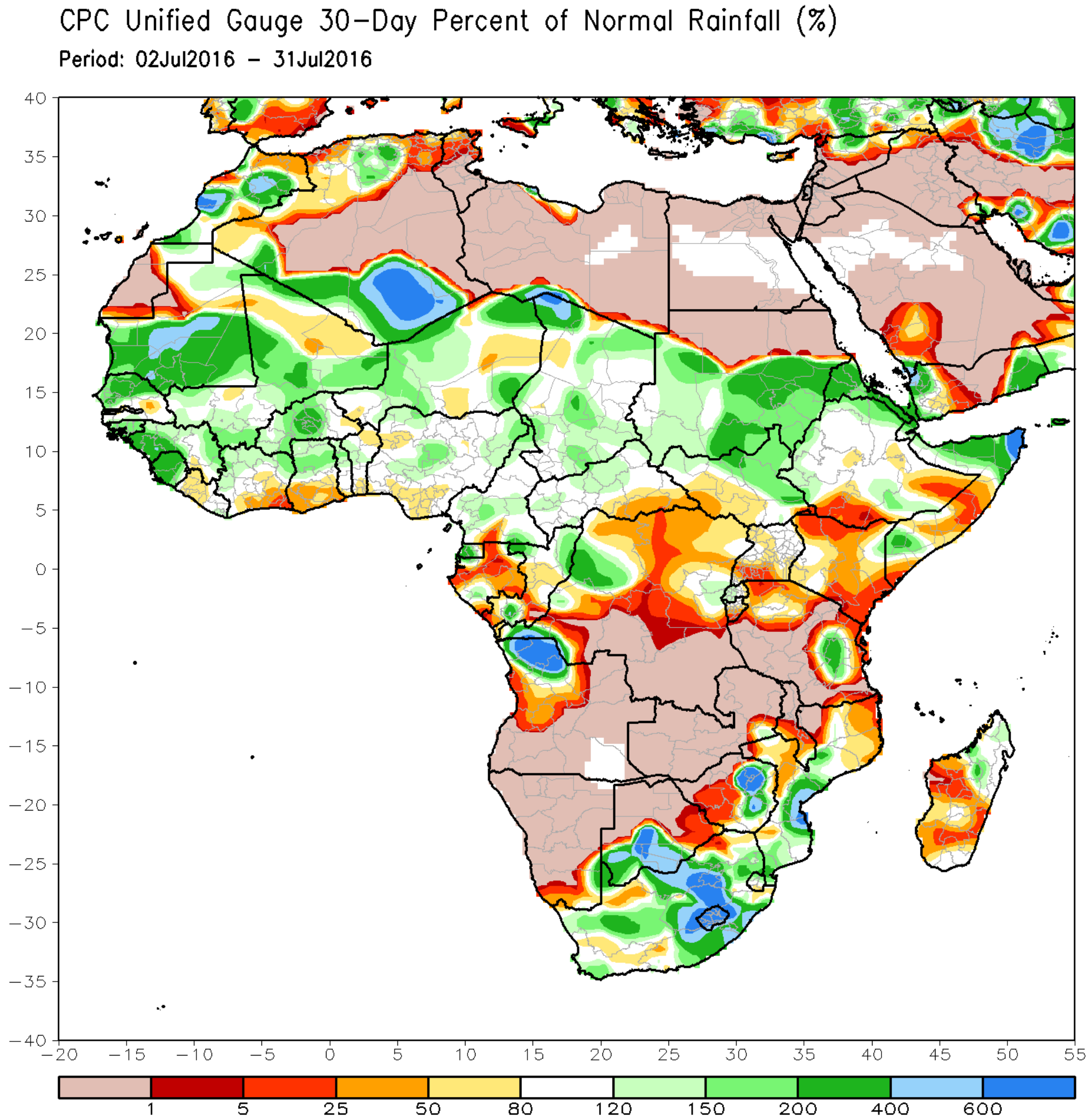

Figure 17: Climate Prediction Center Unified Gauge estimate of percent of normal rainfall from July 2 – July 31, 2016.

8 Atlantic Multi-Decadal Oscillation (AMO)/Thermohaline Circulation (THC) Conditions

One of the big questions that has been asked over the past couple of years is whether we have moved out of the active Atlantic hurricane era We currently monitor the strength of the Atlantic Multidecadal Oscillation (AMO) and Atlantic thermohaline circulation (THC) using a combined proxy measure of SST in the region from 50-60°N, 50-10°W and SLP in the region from 0-50°N, 70-10°W (Figure 18). This index was discussed in detail in Klotzbach and Gray (2008).

We currently weigh standardized values of the index by using the following formula: 0.6*SST – 0.4*SLP. The AMO has been negative every month since November 2014. The July 2016 AMO value was slightly below-average at 0.1 standard deviations less than the 1981-2010 average (Figure 19).

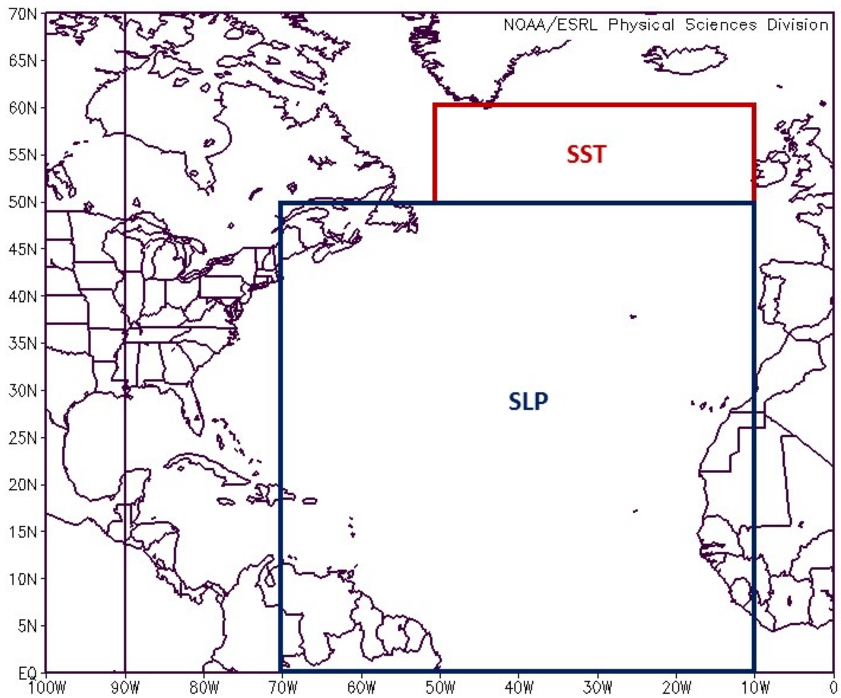

Figure 18: Regions which are utilized for the calculation of our THC/AMO index.

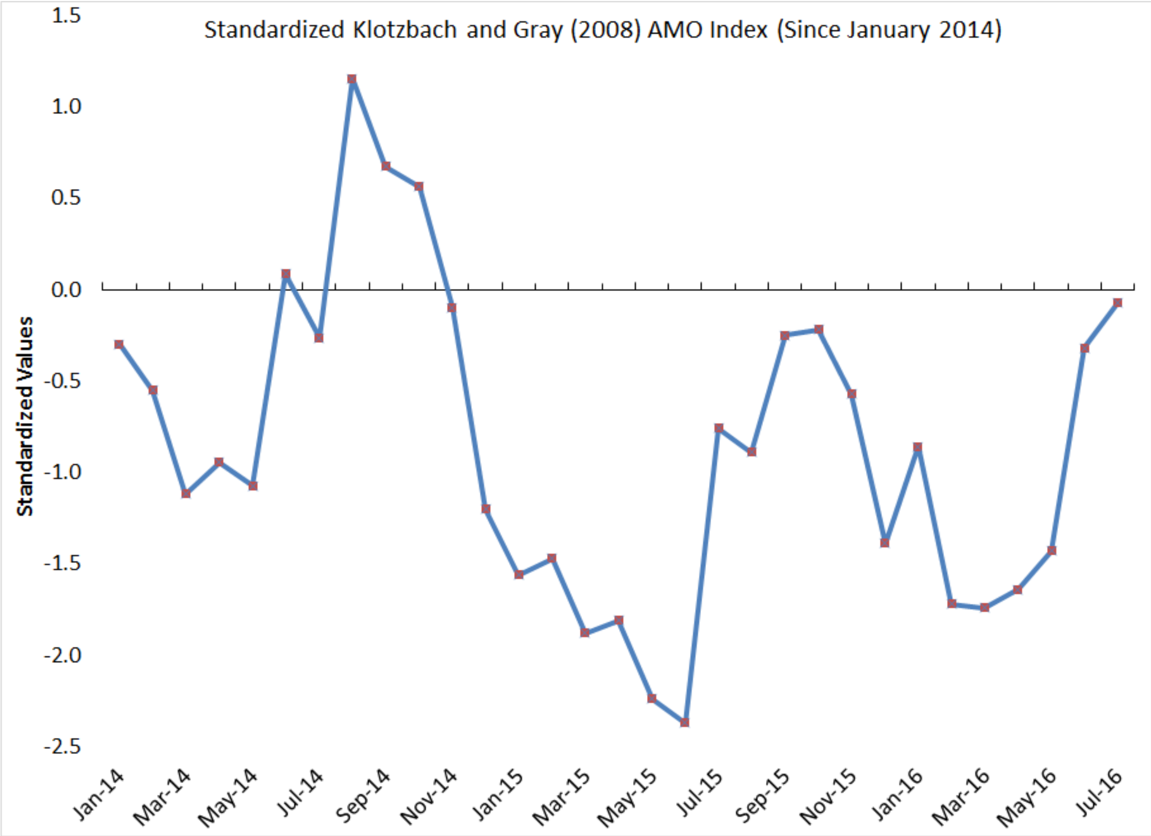

Figure 19: Monthly values of the Klotzbach and Gray (2008) AMO index since January 2014.

9 Adjusted 2016 Forecast

Table 8 shows our final adjusted early August forecast for the 2016 season which is a combination of our statistical scheme (with June-July activity added in), our analog forecast and qualitative adjustments for other factors not explicitly contained in any of these schemes. Our statistical forecast, analog forecast and final qualitative outlook are in good agreement that the remainder of the 2016 Atlantic hurricane season should experience near-average TC activity.

Table 8: June-July 2016 observed activity, our August full season statistical forecast (with June-July 2016 activity added in), our analog forecast and our adjusted final forecast for the 2016 hurricane season.

Forecast Parameter and 1981-2010 Median (in parentheses)	June-July 2016 Observed Activity	Statistical Scheme	Analog Scheme	Adjusted Final Forecast (Whole Season)
Named Storms (12.0)	4	14.5	11.7	**15**
Named Storm Days (60.1)	6.50	57.5	57.6	**55**
Hurricanes (6.5)	1	6.9	6.7	**6**
Hurricane Days (21.3)	1	23.6	27.1	**23**
Major Hurricanes (2.0)	0	2.4	2.3	**2**
Major Hurricane Days (3.9)	0	5.5	5.8	**5**
Accumulated Cyclone Energy Index (92)	6	100	109	**100**
Net Tropical Cyclone Activity (103%)	13	116	113	**110**

10 Landfall Probabilities for 2016

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. Whereas individual hurricane landfall events cannot be forecast months in advance, the total seasonal probability of landfall can be forecast with statistical skill. With the observation that landfall is a function of varying climate conditions, a probability specification has been developed through statistical analyses of all U.S. hurricane and named storm landfall events during the 20th century (1900-1999). Specific landfall probabilities can be given for all tropical cyclone intensity classes for a set of distinct U.S. coastal regions.

Net landfall probability is shown linked to the overall Atlantic basin Net Tropical Cyclone activity (NTC; see Table 9). NTC is a combined measure of the year-to-year mean of six indices of hurricane activity, each expressed as a percentage difference from the long-term average. Long-term statistics show that, on average, the more active the overall Atlantic basin hurricane season is, the greater the probability of U.S. hurricane landfall.

Table 9: NTC activity in any year consists of the seasonal total of the following six parameters expressed in terms of their long-term averages. A season with 10 NS, 50 NSD, 6 H, 25 HD, 3 MH, and 5 MHD would then be the sum of the following ratios: 10/9.6 = 104, 50/49.1 = 102, 6/5.9 = 102, 25/24.5 = 102, 3/2.3 = 130, 5/5.0 = 100, divided by six, yielding an NTC of 107.

	1950-2000 Average	
1)	Named Storms (NS)	9.6
2)	Named Storm Days (NSD)	49.1
3)	Hurricanes (H)	5.9
4)	Hurricane Days (HD)	24.5
5)	Major Hurricanes (MH)	2.3
6)	Major Hurricane Days (MHD)	5.0

Table 10 lists strike probabilities for the 2016 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. Note that Atlantic basin post-1 August NTC activity in 2016 is expected to be near its long-term average, and therefore, landfall probabilities are near their long-term average.

Table 10: Estimated 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) for the remainder of the 2016 Atlantic hurricane season. Probabilities of a tropical storm, hurricane and major hurricane tracking into the Caribbean are also provided. The long-term mean annual probability of one or more landfalling systems during the 20th century is given in parentheses.

Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	78% (79%)	67% (68%)	51% (52%)	84% (84%)	96% (97%)
Gulf Coast (Regions 1-4)	57% (59%)	41% (42%)	29% (30%)	59% (60%)	82% (83%)
Florida plus East Coast (Regions 5-11)	49% (50%)	43% (44%)	30% (31%)	60% (61%)	80% (81%)
Caribbean (10-20°N, 60-88°W)	81% (82%)	56% (57%)	41% (42%)	74% (75%)	95% (96%)

Please also visit the Landfalling Probability Webpage at http://www.e-transit.org/hurricane for landfall probabilities for 11 U.S. coastal regions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine as well as probabilities for every island in the Caribbean.

11 Summary

An analysis of a variety of different atmosphere and ocean measurements (through July) which are known to have long-period statistical relationships with the upcoming season's Atlantic tropical cyclone activity indicate that 2016 should be near its long-term average. Cool neutral ENSO conditions and a somewhat more favorable Atlantic SST pattern should result in a more active season in 2016 than has been experienced in any of the last three years.

12 Forthcoming Updated Forecasts of 2016 Hurricane Activity

We will be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October, beginning today, Thursday, August 4 and continuing every other Thursday (August 18, September 1, etc.). We will be issuing an October-November Caribbean basin forecast on **Friday, 30 September**. A verification and discussion of all 2016 forecasts will be issued in late November 2016. All of these forecasts will be available on the web at: http://hurricane.atmos.colostate.edu/Forecasts.

13 Acknowledgments

Besides the individuals named on page 7, 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.

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15 Verification of Previous Forecasts

Table 11: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity from 2011-2015.

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

2013	10 April	Update 3 June	Update 2 August	Obs.
Hurricanes	9	9	8	2
Named Storms	18	18	18	13
Hurricane Days	40	40	35	3.75
Named Storm Days	95	95	84.25	38.50
Major Hurricanes	4	4	3	0
Major Hurricane Days	9	9	7	0
Accumulated Cyclone Energy	165	165	142	33
Net Tropical Cyclone Activity	175	175	150	44

2014	10 April	Update 2 June	Update 1 July	Update 31 July	Obs.
Hurricanes	3	4	4	4	6
Named Storms	9	10	10	10	8
Hurricane Days	12	15	15	15	17.75
Named Storm Days	35	40	40	40	35
Major Hurricanes	1	1	1	1	2
Major Hurricane Days	2	3	3	3	3.75
Accumulated Cyclone Energy	55	65	65	65	67
Net Tropical Cyclone Activity	60	70	70	70	82

2015	9 April	Update 1 June	Update 1 July	Update 4 August	Obs.
Hurricanes	3	3	3	2	4
Named Storms	7	8	8	8	11
Hurricane Days	10	10	10	8	12.00
Named Storm Days	30	30	30	25	43.75
Major Hurricanes	1	1	1	1	2
Major Hurricane Days	0.5	0.5	0.5	0.5	4
Accumulated Cyclone Energy	40	40	40	35	63
Net Tropical Cyclone Activity	45	45	45	40	81