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

We continue to anticipate that the 2016 Atlantic basin hurricane season will have approximately average activity. The current weakening El Niño is likely to transition to weak La Niña conditions by the peak of the Atlantic hurricane season. While the tropical Atlantic is relatively warm, the far North Atlantic and subtropical northeastern Atlantic are quite cold, 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 1 June 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://hurricane.atmos.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	Observed Activity Through May 2016	Total Seasonal Forecast (Including Alex and Bonnie)*
Named Storms (NS) (12.0)	12	12	2	14
Named Storm Days (NSD) (60.1)	50	50	3	53
Hurricanes (H) (6.5)	5	5	1	6
Hurricane Days (HD) (21.3)	20	20	1	21
Major Hurricanes (MH) (2.0)	2	2	0	2
Major Hurricane Days (MHD) (3.9)	4	4	0	4
Accumulated Cyclone Energy (ACE) (92)	90	90	4	94
Net Tropical Cyclone Activity (NTC) (103%)	95	95	8	103

*TCs Alex and Bonnie formed prior to the start of the hurricane season on 1 June. Over the remainder of the document, our seasonal forecast numbers refer to TCs forming after Alex and Bonnie.

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

1) Entire U.S. coastline - 50% (average for last century is 52%)

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

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

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

1) 40% (average for last century is 42%)

2016 STATE IMPACT PROBABILITIES (NUMBERS IN PARENTHESES ARE LONG-PERIOD AVERAGES)

State	**Hurricane**	**Major Hurricane**
Texas	32% (33%)	11% (12%)
Louisiana	29% (30%)	11% (12%)
Mississippi	10% (11%)	4% (4%)
Alabama	15% (16%)	2% (3%)
Florida	49% (51%)	20% (21%)
Georgia	11% (11%)	1% (1%)
South Carolina	16% (17%)	4% (4%)
North Carolina	27% (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	5% (6%)	2% (3%)
Massachusetts	7% (7%)	2% (2%)
New Hampshire	1% (1%)	<1% (<1%)
Maine	4% (4%)	<1% (<1%)
Whole US	**83% (84%)**	**50% (52%)**

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. In addition, we now include probabilities of named storms, hurricanes and major hurricanes tracking within 50 and 100 miles of various islands and landmasses in the Caribbean and Central America. We suggest that all coastal residents visit the Landfall Probability Webpage for their individual probabilities. We also urge coastal residents to fully prepare for all hurricane seasons, regardless of what our seasonal forecast may be.

ABSTRACT

Information obtained through May 2016 indicates that the 2016 Atlantic hurricane season will have activity near the median 1981-2010 season. We emphasize that there is large uncertainty in this prediction due to the factors that we outline in the following pages.

We estimate that 2016 will have an additional 5 hurricanes (median is 6.5), 12 named storms (median is 12.0), 50 named storm days (median is 60.1), 20 hurricane days (median is 21.3), 2 major (Category 3-4-5) hurricane (median is 2.0) and 4 major hurricane days (median is 3.9). The probability of U.S. major hurricane landfall is estimated to be about 95 percent of the long-period average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2016 to be approximately 90 percent of their long-term averages.

This forecast is based on an extended-range early June statistical prediction scheme that was developed utilizing 29 years of past data. Analog predictors are also utilized. We anticipate an average Atlantic basin hurricane season. While La Niña conditions have the potential to develop over the next few months, the far North Atlantic and subtropical eastern Atlantic are quite cold. These cold anomalies tend to force atmospheric conditions that are less conducive for Atlantic hurricane formation and intensification.

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 extended-range 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 June. 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 early June statistical forecast methodology shows strong evidence over 29 past years that significant improvement over climatology can be attained. We would never issue a seasonal hurricane forecast unless we had a statistical model developed 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.

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.

Indian Ocean Dipole (IOD) - An irregular oscillation of sea surface temperatures between the western and eastern tropical Indian Ocean. A positive phase of the IOD occurs when the western Indian Ocean is anomalously warm compared with the eastern Indian Ocean.

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 major hurricanes form, which we define as 7.5-22.5°N, 75-20°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.

Proxy – An approximation or a substitution for a physical process that cannot be directly measured.

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, 57.5-15°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 June forecast is based on a statistical methodology derived from 29 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 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 of 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.

2 June Forecast Methodology

2.1 June Statistical Forecast Scheme

Our current June statistical forecast model has been built over the period from 1982-2010 to incorporate the most recent and reliable data that is available. It utilizes a total of four predictors. The Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) has been completed from 1979-2010, with a continuation of CFS version 2 data through until present, while the NOAA Optimum Interpolation (OI) SST (Reynolds et al.

2002) is available from 1982-present. This 1 June TC forecast model shows significant skill in predicting levels of Accumulated Cyclone Energy (ACE) activity over the 34-year period from 1982-2015. This hindcast model correlates with ACE at 0.78 during this period.

Table 1 displays ACE hindcasts from 1982-2010, along with real-time forecasts for 2011-2015 using the current statistical scheme, while Figure 1 displays observations versus ACE hindcasts/forecasts. We have correctly predicted above- or below-average seasons in 29 out of 34 hindcast years (85%).   Our predictions have had a smaller error than climatology in 25 out of 34 years (74%). Our average hindcast error is 30 ACE units, compared with 53 ACE units for climatology.

Figure 2 displays the locations of each of our predictors, while Table 2 displays the individual linear correlations between each predictor and ACE over the 1982-2010 hindcast period. All predictors correlate significantly at the 95% level using a two-tailed Student’s t-test and assuming that each year represents an individual degree of freedom. The reader will note that we are incorporating a dynamical SST forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF). Hindcast data provided by Frederic Vitart indicates that the ECMWF model has significant forecast skill for SSTs across the various Nino regions for September from a 1 May forecast date. We utilize the ECMWF ensemble mean prediction for the following September Nino 3 SSTs. Hindcast data from 1982-2010 show that the ECMWF forecast system 3 from 1 May correlates with observed September Nino 3 SSTs at 0.81. ECMWF has upgraded to system 4, which has slightly improved ENSO prediction skill to system 3. Table 3 displays the 2016 observed values for each of the four predictors in the new statistical forecast scheme. The combination of the four predictors calls for a slightly below-average season. Table 4 displays the statistical model output for the combination of the four predictors for the 2016 Atlantic hurricane season.

Table 1: Observed versus early June cross-validated hindcast ACE for 1982-2010 and real-time forecast ACE for 2011-2015 using the current forecast 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 with respect to the 1982-2015 climatology of 103 ACE units, while red bold-faced years in the "Hindcast improvement over Climatology" column are years that we did not beat climatology. The hindcast went the right way with regards to an above- or below-average season in 29 out of 34 years (85%), while hindcast improvement over climatology occurred in 25 out of 34 years (74%).

Year	Observed ACE	Hindcast ACE	Observed minus Hindcast	Observed minus Climatology	Hindcast improvement over Climatology
1982	32	39	-7	-71	64
1983	17	30	-13	-86	73
1984	84	91	-7	-19	12
1985	88	84	4	-15	11
1986	36	57	-21	-67	46
1987	34	43	-9	-69	60
1988	103	132	-29	0	**-29**
1989	135	135	0	32	32
1990	97	**134**	-37	-6	**-31**
1991	36	37	-1	-67	66
1992	76	54	22	-27	4
1993	39	40	-1	-64	63
1994	32	43	-11	-71	60
1995	227	217	10	124	114
1996	166	156	10	63	53
1997	41	73	-32	-62	30
1998	182	148	34	79	45
1999	177	139	38	74	36
2000	119	**97**	22	16	**-6**
2001	110	143	-33	7	**-26**
2002	67	36	31	-36	4
2003	176	142	34	73	39
2004	227	125	102	124	22
2005	250	155	95	147	52
2006	79	**142**	-63	-24	**-39**
2007	74	**144**	-70	-29	**-41**
2008	146	162	-16	43	27
2009	53	57	-4	-50	46
2010	163	211	-48	60	12
2011	126	159	-33	23	**-10**
2012	133	106	27	30	3
2013	36	**125**	-89	-67	**-22**
2014	67	69	-2	-36	34
2015	63	15	48	-40	**-8**
Average	**103**	**104**	**|30|**	**|53|**	**+23**

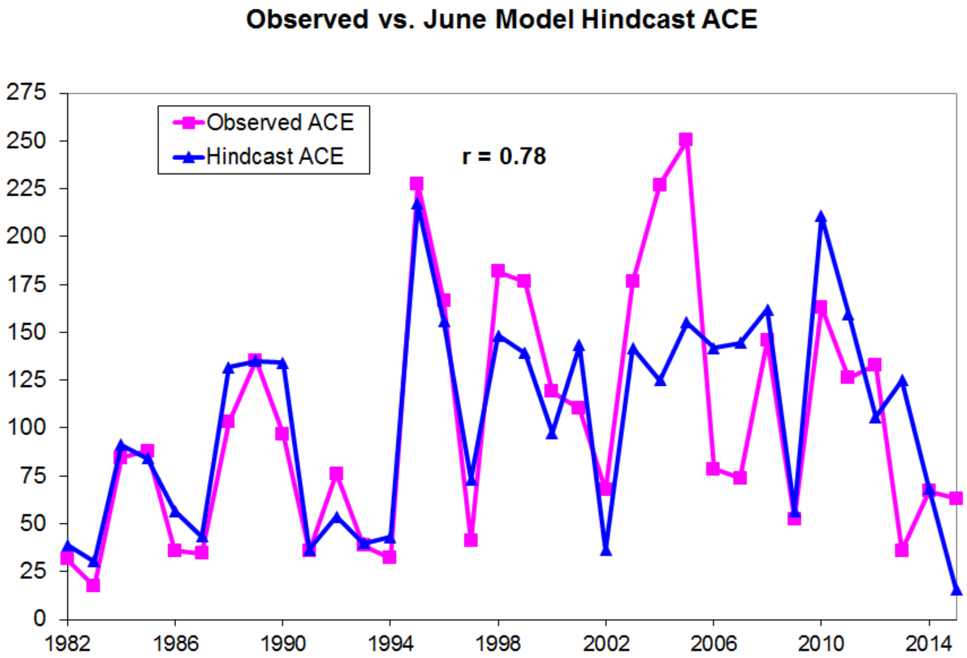


Figure 1: Observed versus early June hindcast values of ACE for 1982-2015. The hindcast model explains approximately 60% of the variance from climatology.

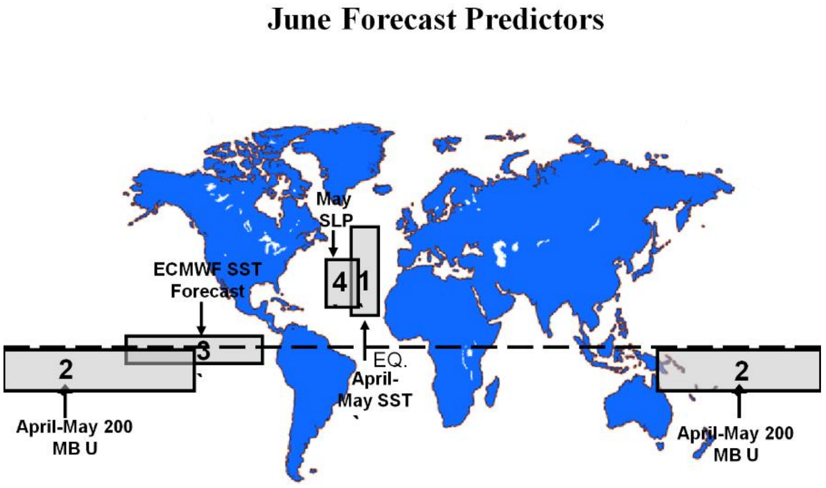


Figure 2: Location of predictors for our early June extended-range statistical prediction for the 2016 hurricane season. Predictor 2 spans both sides of the International Date Line.

Table 2: Linear correlation between each 1 June predictor and ACE over the 1982-2015 hindcast period. For more ACE activity, the sign of predictors 1 and 2 should be positive, while the sign of predictors 3 and 4 should be negative.

Predictor	**Correlation w/ ACE**
1) April-May SST (15-55°N, 15-35°W) (+)	0.54
2) April-May 200 MB U (0-15°S, 150°E-120°W) (+)	0.52
3) ECMWF 1 May SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.48
4) May SLP (20-40°N, 30-50°W) (-)	-0.47

Table 3: Listing of 1 June 2016 predictors for the 2016 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity. The combination of the four predictors calls for a slightly below-average Atlantic hurricane season.

Predictor	**2016 Forecast Value**
1) April-May SST (15-55°N, 15-35°W) (+)	-0.3 SD
2) April-May 200 MB U (0-15°S, 150°E-120°W) (+)	0.0 SD
3) ECMWF 1 May SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.5 SD
4) May SLP (20-40°N, 30-50°W) (-)	+1.7 SD

Table 4: Statistical model output for the 2016 Atlantic hurricane season.

Forecast Parameter and 1981-2010 Median (in parentheses)	Statistical Forecast
Named Storms (12.0)	10.1
Named Storm Days (60.1)	47.9
Hurricanes (6.5)	5.6
Hurricane Days (21.3)	20.8
Major Hurricanes (2.0)	2.2
Major Hurricane Days (3.9)	4.8
Accumulated Cyclone Energy Index (92)	85
Net Tropical Cyclone Activity (103%)	95

2.2 Physical Associations among Predictors Listed in Table 2

The locations and brief descriptions of the predictors for our early June statistical forecast are now discussed. All of these factors are generally related to August-October vertical wind shear in the Atlantic Main Development Region (MDR) from 10-20°N, 20-70°W as shown in Figure 3.

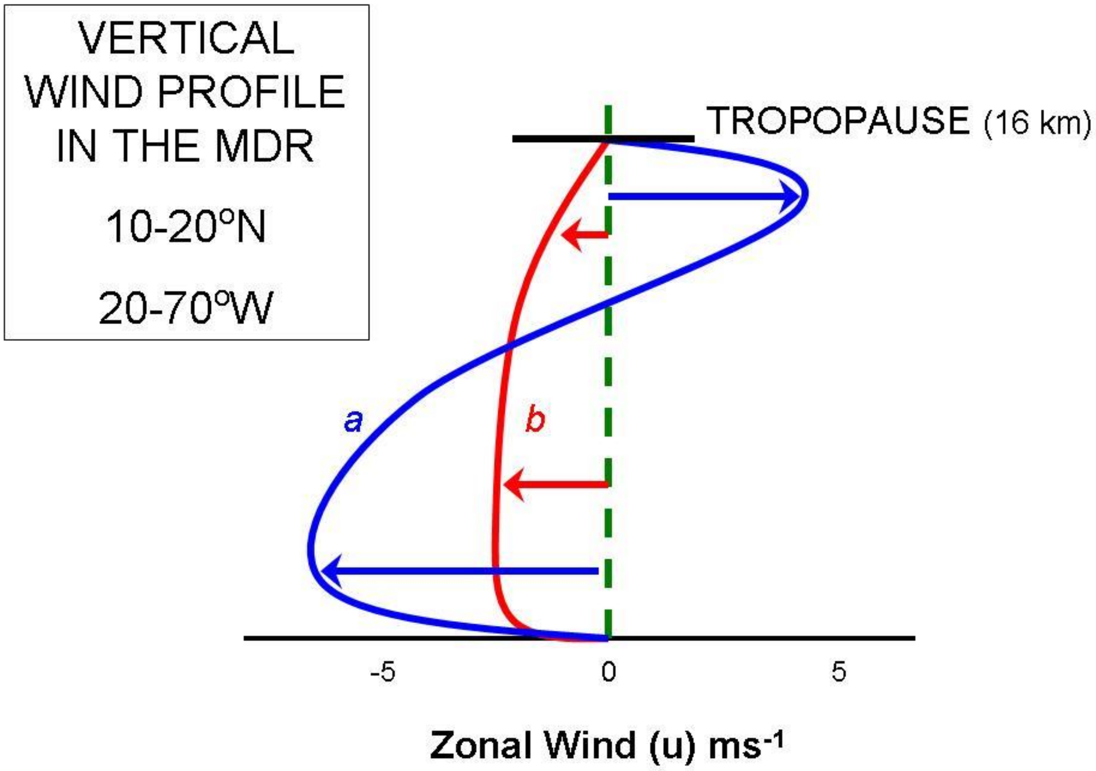


Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of tropospheric vertical wind shear.

For each of these predictors, we display a four-panel figure showing linear correlations between values of each predictor and August-October values of sea surface temperature (SST), sea level pressure, 200 mb zonal wind, and 850 mb zonal wind, respectively. In general, higher values of SSTs, lower values of SLPA, anomalous westerlies at 850 mb and anomalous easterlies at 200 mb are associated with active Atlantic basin hurricane seasons. SST correlations are displayed using the NOAA Optimum Interpolation (OI) SST, while SLP, 850 mb, and 200 mb zonal wind correlations are displayed using the Climate Forecast System Reanalysis (CFSR).

Predictor 1. April-May SST in the Eastern Atlantic (+)

(15-55°N, 15-35°W)

Warmer-than-normal SSTs in the eastern Atlantic during the April-May period are associated with a weaker-than-normal subtropical high and reduced trade wind strength during the boreal spring (Knaff 1997). Positive SST anomalies in April-May are correlated with weaker trade winds and weaker upper tropospheric westerly winds, lower-than-normal sea level pressures and above-normal SSTs in the tropical Atlantic during the following August-October period (Figure 4). All three of these August-October features are commonly associated with active Atlantic basin hurricane seasons, through reductions in vertical wind shear, increased vertical instability and increased mid-tropospheric moisture, respectively. Predictor 1 correlates quite strongly (~0.6) with NTC. Predictor 1 also strongly correlates (r = 0.65) with August-October values of the Atlantic Meridional Mode (AMM) (Kossin and Vimont 2007) over the period from 1982-2010. The AMM has been shown to impact Atlantic hurricane activity through alterations in the position and intensity of the Atlantic Inter-Tropical Convergence Zone (ITCZ). Changes in the Atlantic ITCZ bring about changes in tropical Atlantic vertical and horizontal wind shear patterns and in tropical Atlantic SST patterns.

Predictor 2. April-May 200-mb zonal winds in the south-central Tropical Pacific (+)

(0-15°S, 150°E-120°W)

Anomalous upper-level westerly zonal winds in the south-central tropical Pacific are typically associated with ongoing La Niña conditions and a strong Walker Circulation. The spring months are the climatologically favored time for ENSO events to transition from one phase to another (e.g., El Niño to La Niña or vice versa). If the atmosphere is strongly locked into the La Niña phase as evidenced by anomalously strong upper-level westerly winds, the odds of transitioning to an El Niño are reduced. Figure 5 shows that positive values of this predictor are also associated with favorable hurricane formation conditions in the tropical Atlantic, including above-average SSTs and below-average SLPs and zonal wind shear.

Predictor 3. ECMWF 1 May SST Forecast for September Nino 3 (-)

(5°S -5°N, 90-150°W)

The ECMWF seasonal forecast system 3 has shown skill at being able to forecast SST anomalies associated with ENSO several months into the future (Stockdale et al. 2011). ECMWF has recently upgraded their seasonal forecast model to system 4. ENSO has been documented in many studies to be one of the primary factors associated with interannual fluctuations in Atlantic basin and U.S. landfalling hurricane activity (Gray 1984, Goldenberg and Shapiro 1996, Bove et al. 1998, Klotzbach 2011), primarily through alterations in vertical wind shear patterns. The ensemble-averaged ENSO forecast for September values of the Nino 3 region from a 1 May issue date correlates with observations at 0.81. When the ECMWF model predicts cool SST anomalies for September, it strongly correlates with observed cool anomalies throughout the tropical Pacific associated with La Niña conditions, as well as reduced vertical wind shear, especially across the Caribbean (Figure 6).

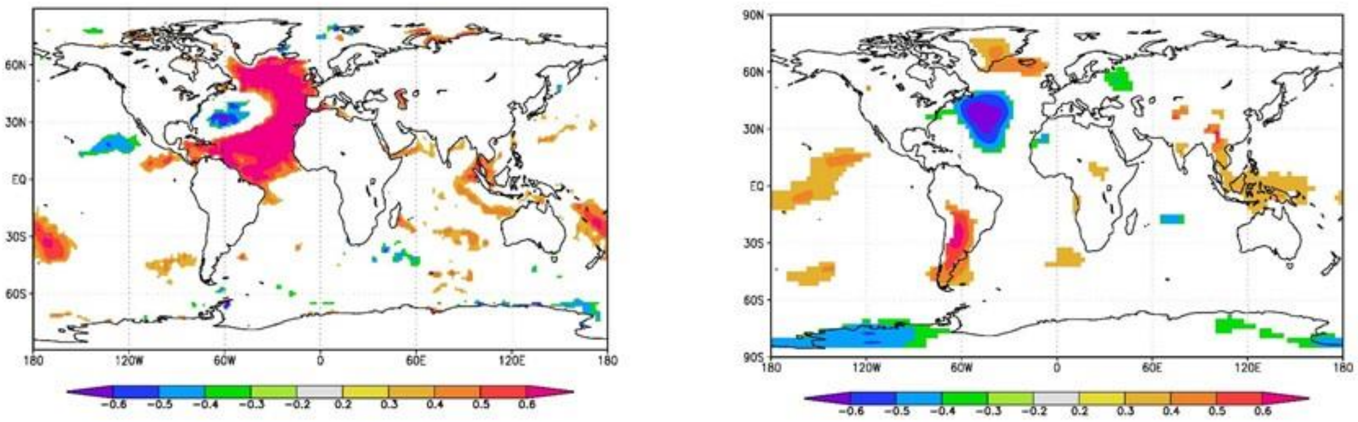
Predictor 4. May SLP in the central Atlantic (-)

(20-40°N, 30-50°W)

Low pressure during the month of May in the central Atlantic is associated with reduced trade wind strength across the tropical Atlantic. This reduced trade wind strength promotes reduced upwelling, mixing and enhances ocean current flow from the south, all of which promote the development or sustenance of warm anomalies in the tropical Atlantic. These warm anomalies tend to persist throughout the peak months of the hurricane season (Figure 7). Also, upper-level easterly anomalies in the Caribbean are associated with low values of this predictor.

(a) SST

(b) SLP



(c) 850 mb U

(d) 200 mb U

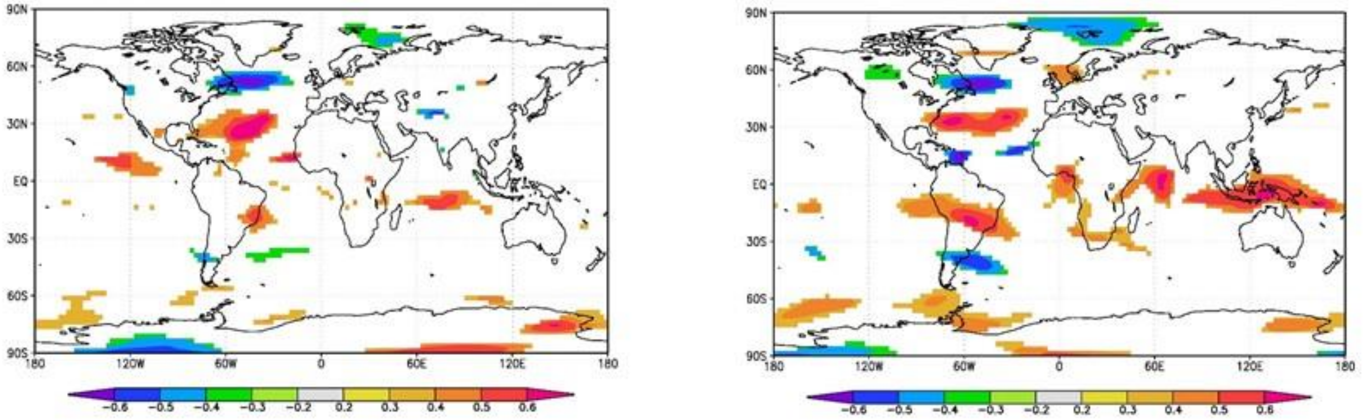
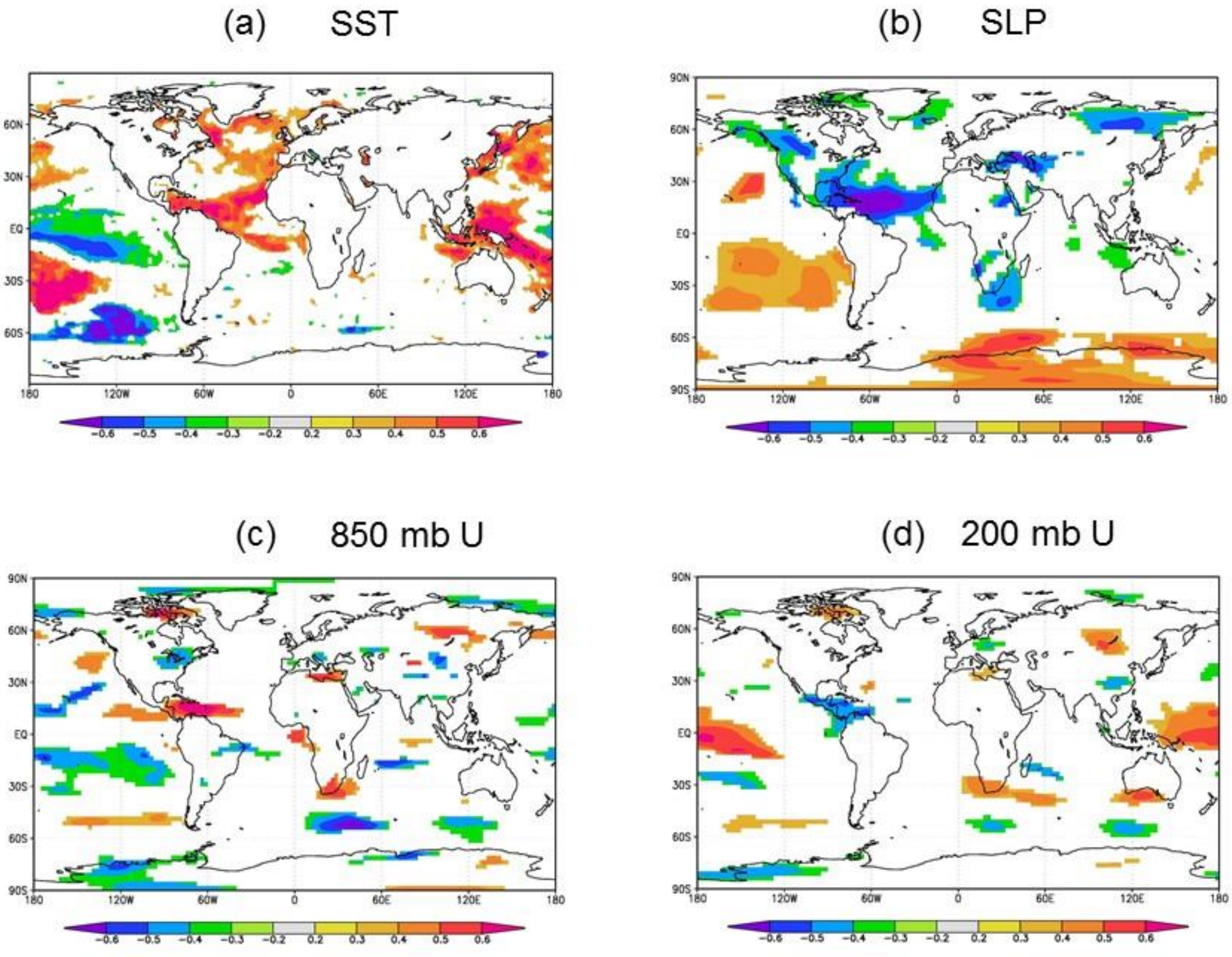


Figure 4: Linear correlations between April-May SST in the eastern Atlantic (Predictor 1) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following August-October 200 mb zonal wind (panel d). All four of these parameter deviations in the tropical Atlantic are known to be favorable for enhanced hurricane activity.



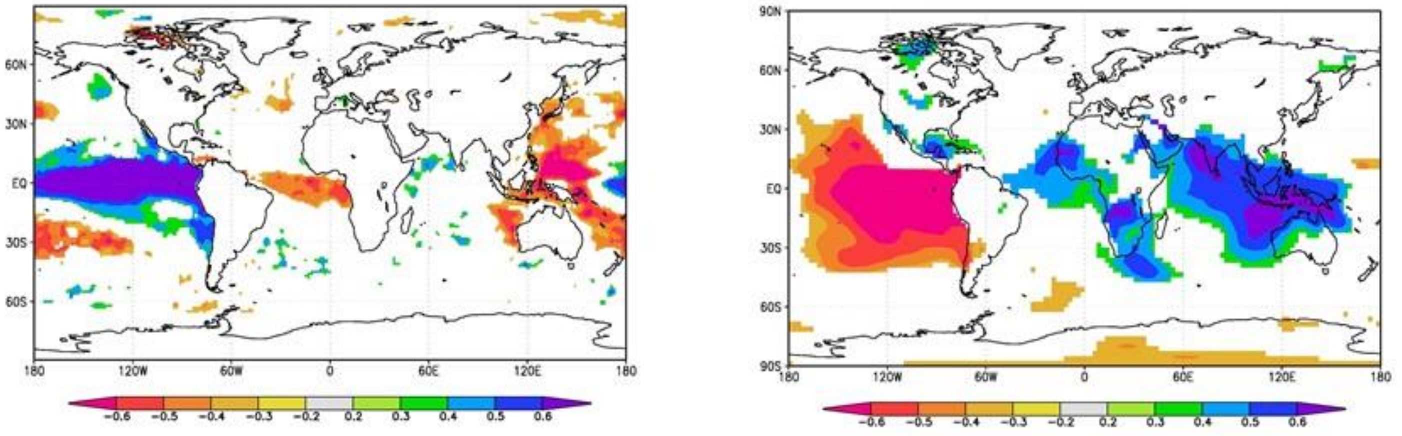
(a) SST

(b) SLP

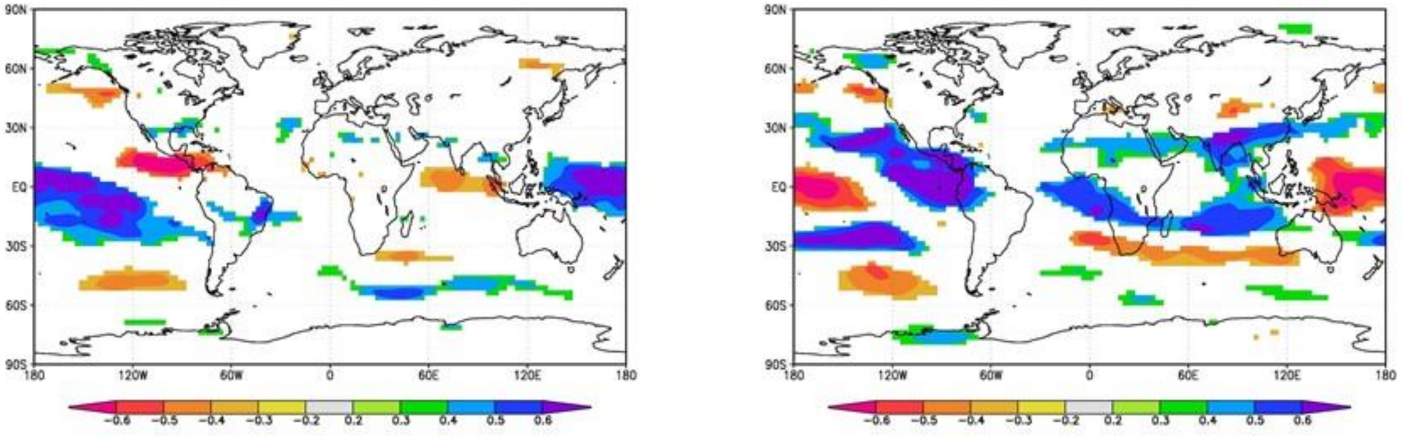
(c) 850 mb U

(d) 200 mb U

Figure 5: Linear correlations between April-May 200-mb zonal winds in the south-central tropical Pacific (Predictor 2) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following August-October 200 mb zonal wind (panel d). All of these parameter deviations over the tropical Atlantic and tropical Pacific tend to be associated with active hurricane seasons.


(a) SST

(b) SLP


(c) 850 mb U

(d) 200 mb U

Figure 6: Linear correlations between a 1 May ECMWF SST forecast for September Nino 3 (Predictor 3) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following August-October 200 mb zonal wind (panel d). The predictor correlates very strongly with ENSO as well as vertical shear in the Caribbean. The correlation scale has been flipped to allow for easy comparison of correlations for all four predictors.

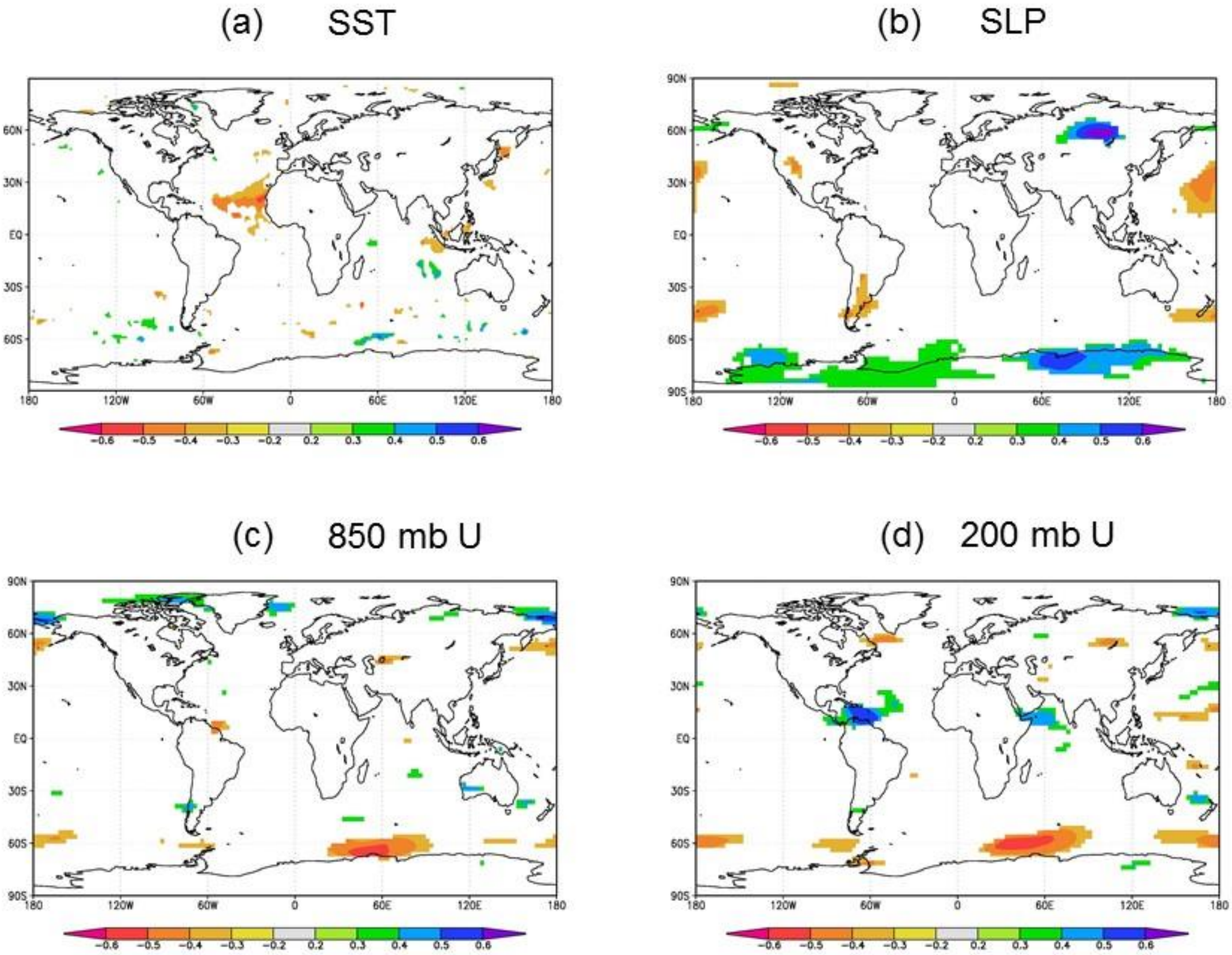


Figure 7: Linear correlations between May sea level pressure in the central Atlantic (Predictor 4) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following August-October 200 mb zonal wind (panel d). The correlation scale has been flipped to allow for easy comparison of correlations for all four predictors.

3 Forecast Uncertainty

One of the questions that we are asked regarding our seasonal hurricane predictions is the degree of uncertainty that is involved. 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 early June forecasts, with error bars based on one standard deviation of the 1982-2010 cross-validated hindcast error. 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 2016 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

Parameter	Hindcast Error (SD)	2016 Forecast	Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range)
Named Storms (NS)	3.7	12	8.3 – 15.7
Named Storm Days (NSD)	21.1	50	28.9 – 71.1
Hurricanes (H)	2.1	5	2.9 – 7.1
Hurricane Days (HD)	10.2	20	9.8 – 30.2
Major Hurricanes (MH)	1.6	2	0.4 – 3.6
Major Hurricane Days (MHD)	5.3	4	0.0 – 9.3
Accumulated Cyclone Energy (ACE)	48	90	42 – 138
Net Tropical Cyclone (NTC) Activity	48	95	47 – 143

4 Analog-Based Predictors for 2016 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2016. These years also provide useful clues as to likely trends in activity that the forthcoming 2016 hurricane season may bring. For this early June extended range forecast, we determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current April-May 2016 conditions. Table 6 lists our analog selections.

We select prior hurricane seasons since 1950 which have similar atmospheric-oceanic conditions to those currently being experienced. We searched for years that were characterized by El Niño the previous winter and were transitioning to either neutral or La Niña conditions and generally had cool SST anomalies in the far North Atlantic and near-average tropical Atlantic SSTs during the upcoming hurricane season.

There were five hurricane seasons since 1950 with characteristics most similar to what we expect to see in August-October of 2016. We anticipate that the 2016 hurricane season will have slightly more activity than the average of our five analog years, given that the tropical Atlantic is currently warmer than the average of these five years. We believe that this season should experience near-average activity.

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
1973	8	37.75	4	10.00	1	0.25	48	53
1978	11	40.50	5	13.50	2	3.50	62	82
1983	4	14.50	3	3.50	1	0.25	17	31
1992	7	40.25	4	16.00	1	3.50	76	67
2003	16	81.50	7	32.75	3	16.75	176	175
Average	9.2	42.9	4.6	15.2	1.7	4.9	76	81
2016 Forecast	**12**	**50**	**5**	**20**	**2**	**4**	**90**	**95**

5 ENSO

Strong El Niño conditions were present during the winter of 2015/2016. Upper ocean heat content (top 300 meters) anomalies have decreased rapidly in recent weeks and are now below-average, indicative of a weakening El Niño event and a potential transition to La Niña (Figure 8). SST anomalies in several of the regions used to define El Niño events have dropped below the 0.5°C threshold typically required for El Niño conditions in recent weeks.

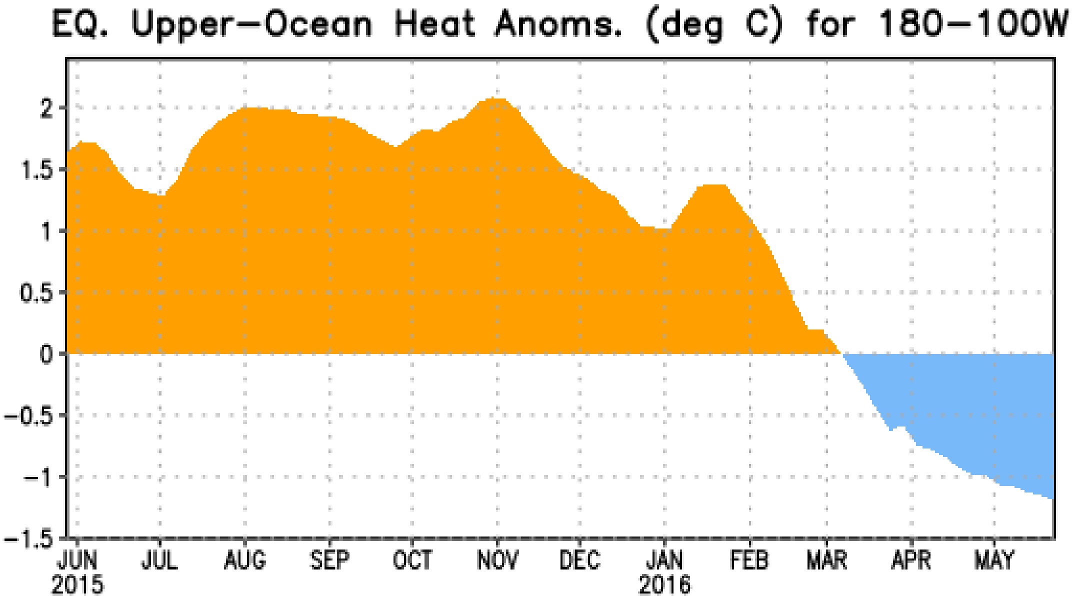


Figure 8: Central and eastern tropical Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Anomalies have steadily decreased since peaking in December.

Currently, SSTs are running near average across most of the eastern and central tropical Pacific. Table 7 displays March and May SST anomalies for several of the Nino regions. The tropical Pacific has cooled considerably during the two-month period, consistent with the transition away from strong El Niño conditions.

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

Region	March SST Anomaly (°C)	May SST Anomaly (°C)	May – March SST Anomaly (°C)
Nino 1+2	+0.9	+0.3	-0.6
Nino 3	+1.6	+0.1	-1.5
Nino 3.4	+1.7	+0.4	-1.3
Nino 4	+1.3	+0.6	-0.7

There is still considerable uncertainty as to what ENSO conditions will look like during the peak of the Atlantic hurricane season from August-October. The spring months are known for their ENSO predictability barrier. While we are nearing the end of this predictability barrier, considerable changes in ENSO often take place in June and July. Both statistical and dynamical models show improved skill by the end of May for the August-October period when compared with their skill at the end of March. These models show even better skill by the end of June and July. Most of the dynamical model guidance is calling for a transition to weak or moderate La Niña conditions by the peak of the Atlantic hurricane season (Figure 9).

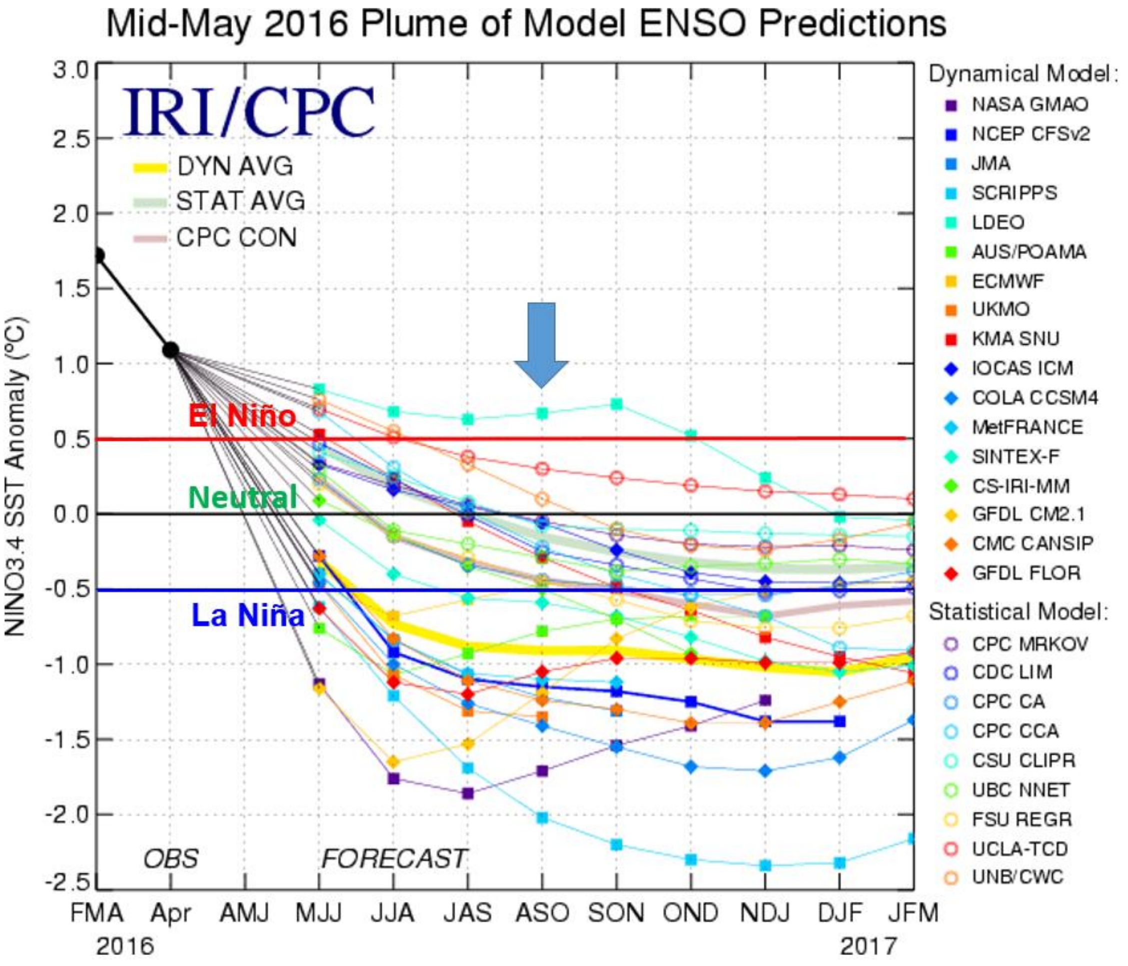


Figure 9: ENSO forecasts from various statistical and dynamical models. Figure courtesy of the International Research Institute (IRI). Most dynamical models call for a weak to moderate La Niña over the next several months.

We find that, in general, the European Centre for Medium-Range Weather Forecasts (ECMWF) shows the best prediction skill of the various ENSO models. The correlation skill between a 1 May forecast from the ECMWF model system 3 and the observed September Nino 3.4 anomaly is 0.82, based on hindcasts/forecasts from 1982-2010, explaining approximately 65% of the variance in Nino 3.4 SST. The ECMWF has upgraded to system 4, which appears to have even better skill than the previous version. The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately -0.5°C. There is a fairly wide spread in the outcomes predicted by the various ensemble members, which indicates the large degree of uncertainty in future ENSO conditions (Figure 10).

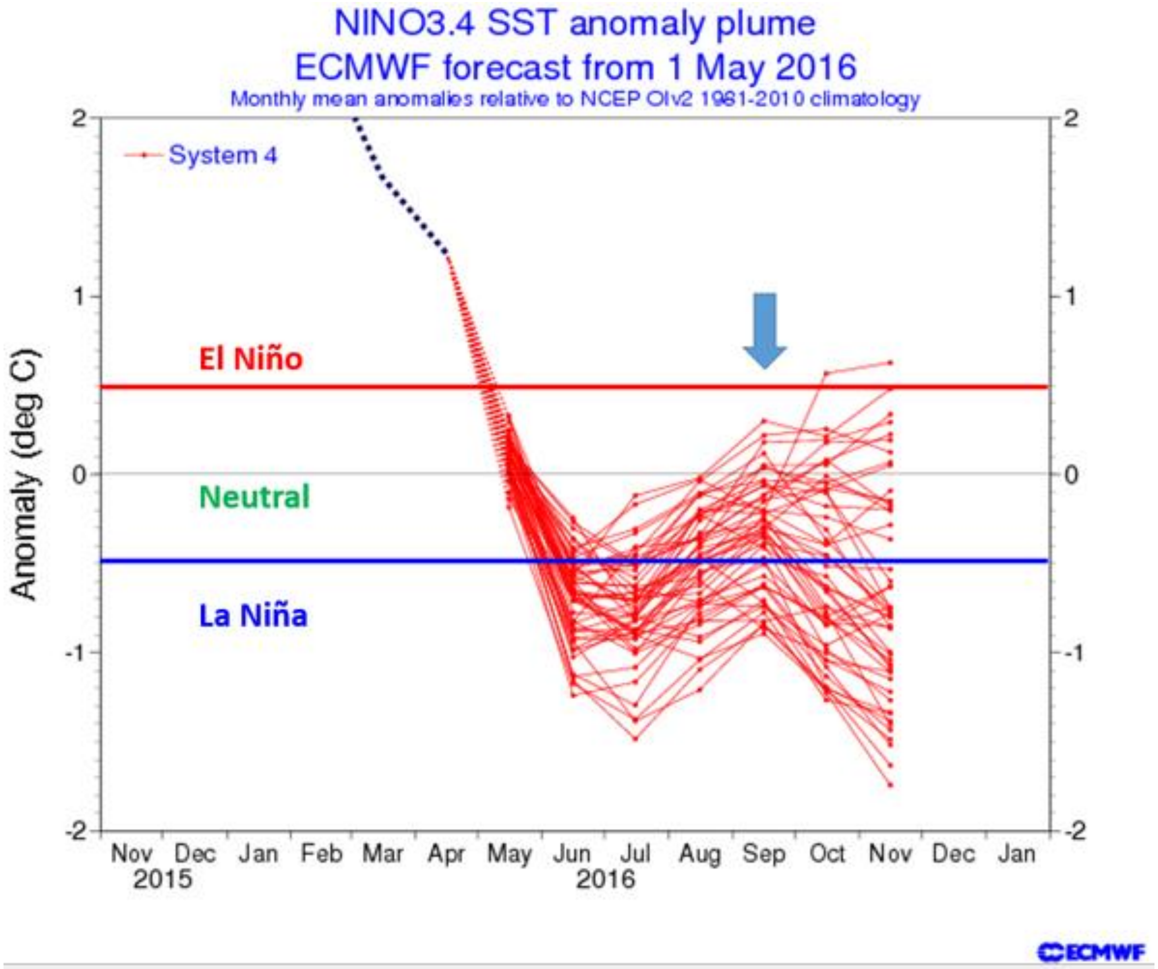


Figure 10: ECMWF ensemble model forecast for the Nino 3.4 region.

Our confidence that El Niño will dissipate and likely transition to La Niña conditions has grown since early April. Upper-ocean heat content anomalies are now below average across the entire tropical Pacific, indicating that the strong El Niño that just occurred discharged significant heat away from the tropical Pacific (Figure 11).

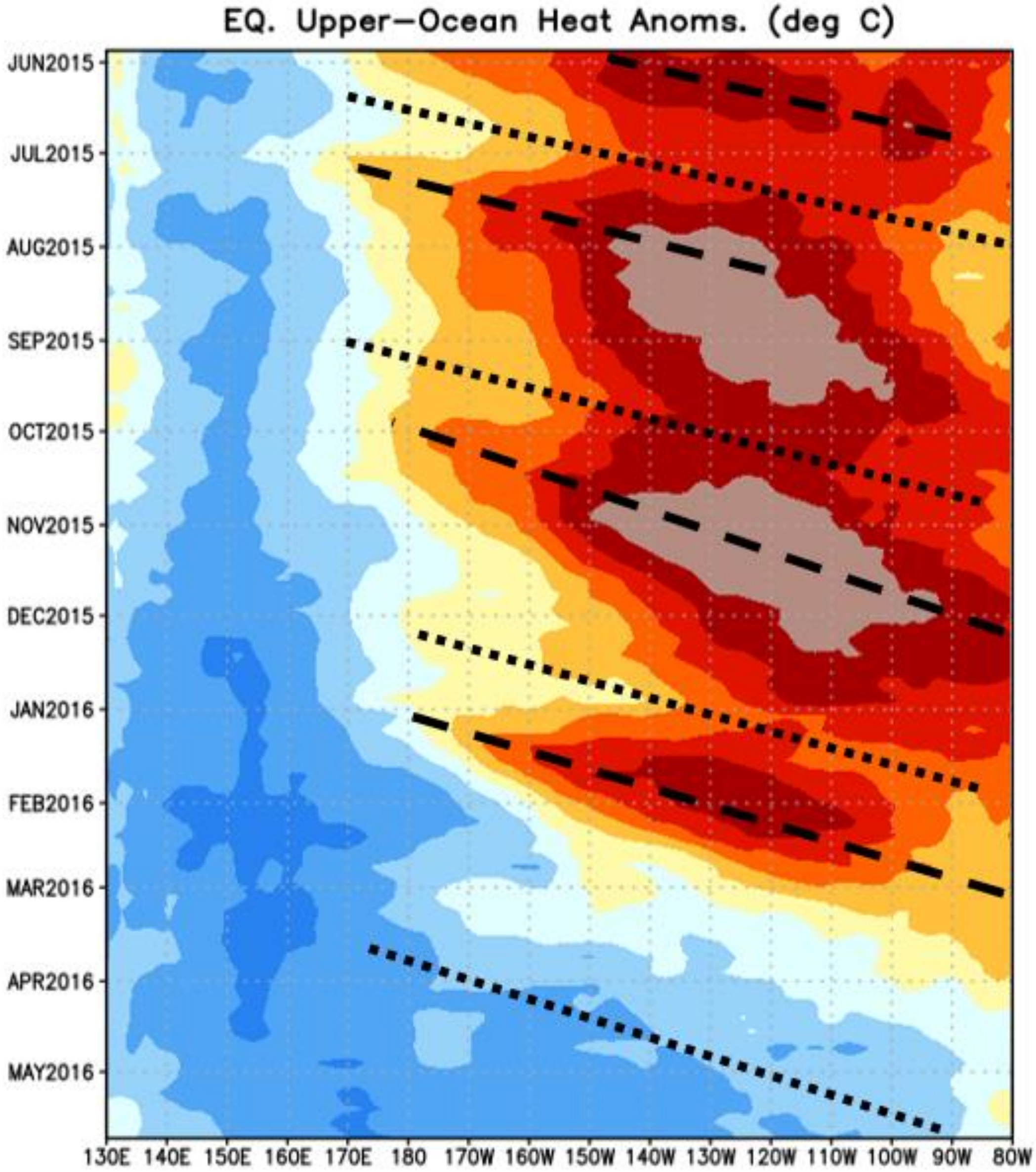


Figure 11: Upper-ocean heat content anomalies across the tropical Pacific. Note that the entire tropical Pacific is presently characterized by below-normal heat content anomalies, indicative that a transition to La Niña is likely. Dashed lines represent the warming (downwelling) phase of the Kelvin wave, while the dotted lines represent the cooling (upwelling) phase of the Kelvin wave.

Based on the above information, we are currently anticipating a weak La Niña event for this year's Atlantic hurricane season. There remains a need to closely monitor ENSO conditions over the next few months. Additional discussion of ENSO will be included with the July 1 and August 4 updates.

6 Current Atlantic Basin Conditions

As has been the case for the past several years, the overall SST pattern across the North Atlantic somewhat represents a negative phase of the AMO (Figure 12). The far North Atlantic currently has SSTs at near record cold levels. SSTs are also below-average in the eastern part of the subtropical Atlantic. However, SSTs in the tropical Atlantic are somewhat above average at present. In May, however, SSTs in the eastern subtropical Atlantic and far North Atlantic correlate at higher levels with seasonal ACE values than do tropical Atlantic SSTs (Figure 13). This is likely due to the fact that cold SSTs in the far North Atlantic and subtropical eastern Atlantic tend to force higher subtropical pressures and consequent stronger trade winds that then cool the tropical Atlantic by the peak of the Atlantic hurricane season. Very strong high pressure was observed across most of the subtropical and tropical Atlantic during May (Figure 14).

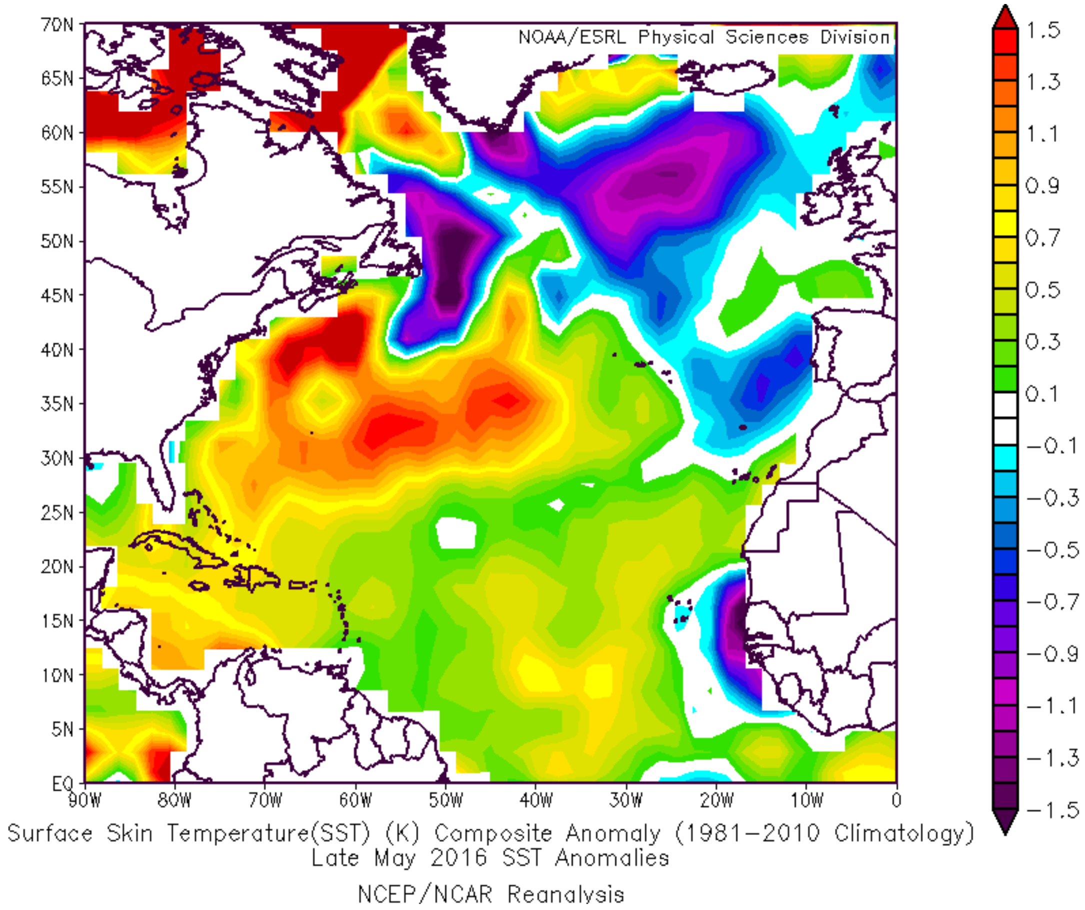


Figure 12: Late May 2016 SST anomalies across the Atlantic.

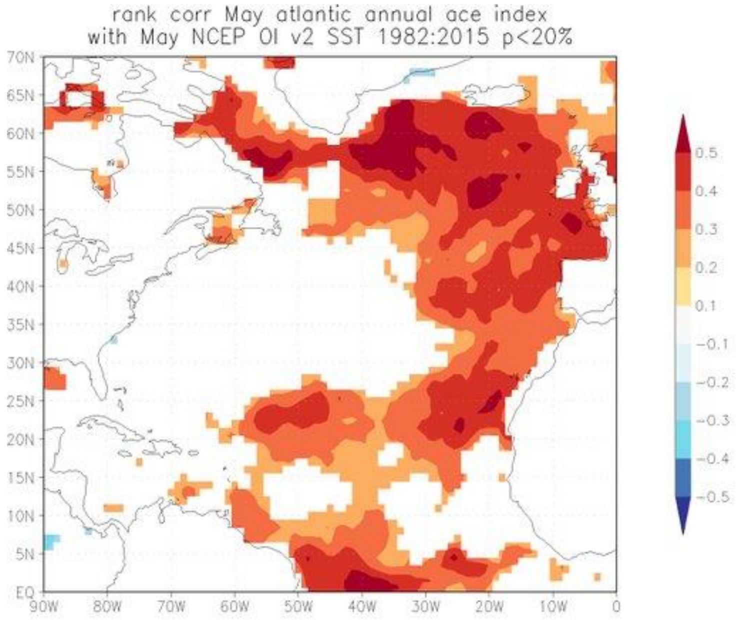


Figure 13: Correlation between Atlantic basin ACE and May North Atlantic SSTs over the period from 1982-2015. Note that the strongest correlations are in the far North Atlantic and subtropical eastern Atlantic.

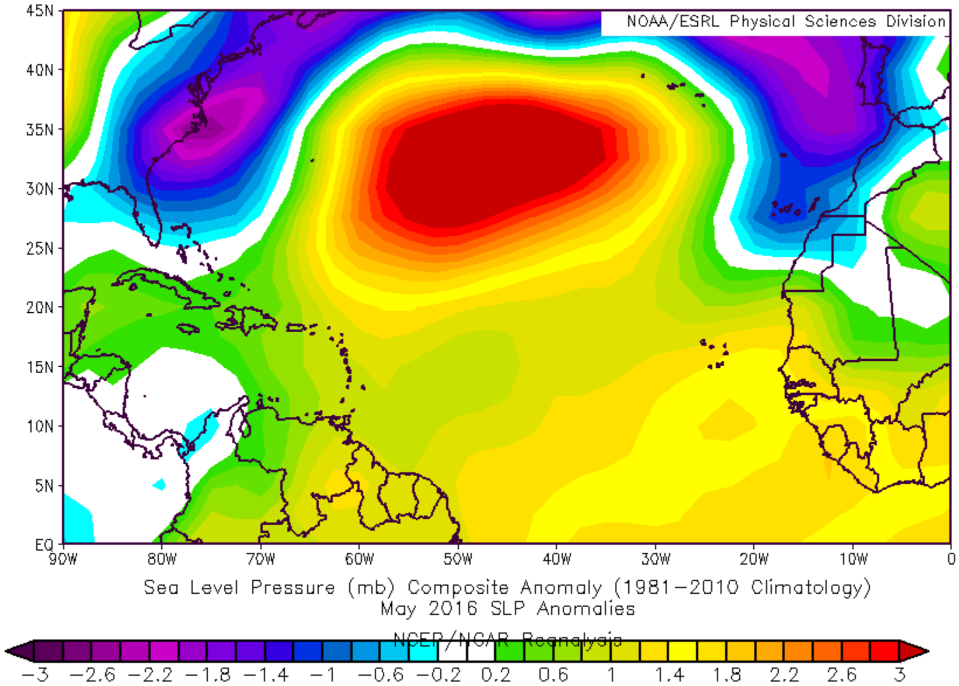


Figure 14: Sea level pressure anomalies during May 2016. Sea level pressure anomalies were generally well above average across the tropical and subtropical North Atlantic.

7 Current THC/AMO Strength

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 15). 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, and we estimate that our AMO index will be at very low levels in May 2016 as well.

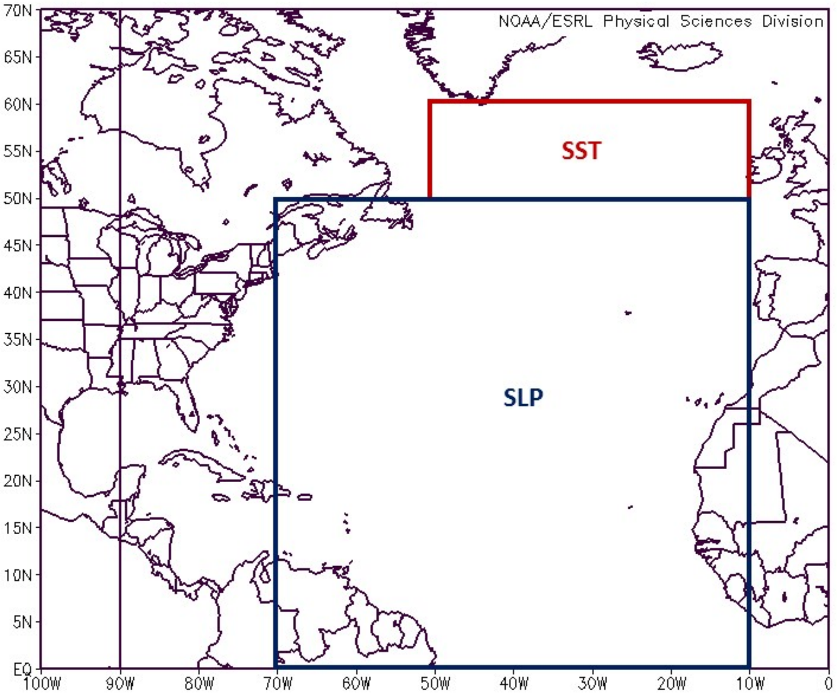


Figure 15: Regions which are utilized for the calculation of our THC/AMO index.

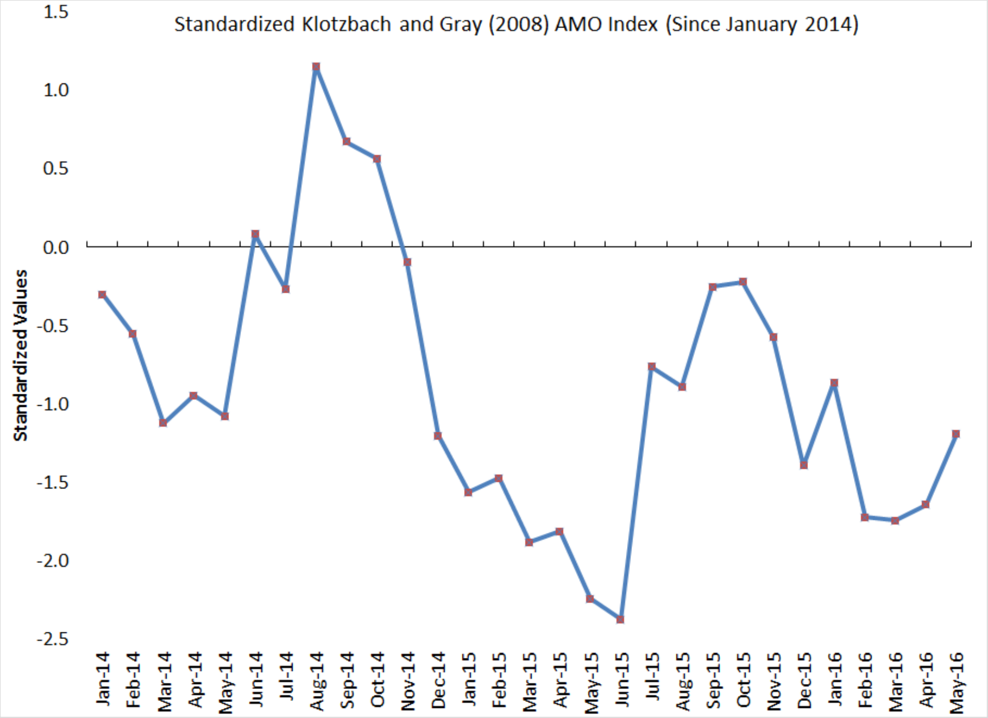


Figure 16: Monthly values of the Klotzbach and Gray (2008) AMO index since January 2014. May 2016's value is estimated with data through May 27. The final May value will be posted online in a couple of days.

8 Adjusted 2016 Forecast

Table 9 shows our final adjusted early June forecast for the 2016 season which is a combination of our statistical scheme, our analog scheme and qualitative adjustments for other factors not explicitly contained in any of these schemes. Both the statistical and analog schemes call for slightly below-average activity. Overall, we are predicting a near-average season for the Atlantic basin in 2016 due to two factors that at this point we anticipate to nearly cancel each other. A likely developing La Niña should lead to more conducive conditions for Atlantic hurricane formation, but a cold far North and cold subtropical eastern Atlantic should lead to less conducive conditions for Atlantic hurricane formation.

Table 9: Summary of our early June statistical forecast, our analog forecast and our adjusted final forecast for the 2016 hurricane season.

Forecast Parameter and 1981-2010 Median (in parentheses)	Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (12.0)	10.1	9.2	12
Named Storm Days (60.1)	47.9	42.9	50
Hurricanes (6.5)	5.6	4.6	5
Hurricane Days (21.3)	20.8	15.2	20
Major Hurricanes (2.0)	2.2	1.7	2
Major Hurricane Days (3.9)	4.8	4.9	4
Accumulated Cyclone Energy Index (92)	85	76	90
Net Tropical Cyclone Activity (103%)	95	81	95

9 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 10). 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 10: NTC activity in any year consists of the seasonal total of the following six parameters expressed in terms of their long-term percentage deviation from average. 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 now issue probabilities for various islands and landmasses in the Caribbean and in Central America. Note that Atlantic basin NTC activity in 2016 is expected to be near its long-term average of 100, 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 2016. 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 last 100 years 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)	77% (79%)	66% (68%)	50% (52%)	83% (84%)	96% (97%)
Gulf Coast (Regions 1-4)	57% (59%)	41% (42%)	29% (30%)	58% (60%)	82% (83%)
Florida plus East Coast (Regions 5-11)	49% (50%)	42% (44%)	30% (31%)	59% (61%)	79% (81%)
Caribbean (10-20°N, 60-88°W)	81% (82%)	55% (57%)	40% (42%)	73% (75%)	95% (96%)

10 Summary

An analysis of a variety of different atmosphere and ocean measurements (through May) which are known to have long-period statistical relationships with the upcoming season's Atlantic tropical cyclone activity indicate that 2016 should be near average. The big question marks with this season's predictions are how quickly the tropical Pacific transitions to La Niña, as well as what the configuration of SSTs will look like in the tropical and far North Atlantic Ocean during the peak of the Atlantic hurricane season.

11 Forthcoming Updated Forecasts of 2016 Hurricane Activity

We will be issuing seasonal updates of our 2016 Atlantic basin hurricane forecasts on **Friday 1 July and Thursday 4 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 2016 forecasts will be issued in late November 2016. All of these forecasts will be available on our website at: http://hurricane.atmos.colostate.edu/Forecasts.

12 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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14 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