EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2017

We anticipate that the 2017 Atlantic basin hurricane season will have slightly below-average activity. The current neutral ENSO is likely to transition to either weak or moderate El Niño conditions by the peak of the Atlantic hurricane season. The tropical Atlantic has anomalously cooled over the past month and the far North Atlantic is relatively cold, potentially indicative of a negative phase of the Atlantic Multi-Decadal Oscillation. We anticipate a below-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 6 April 2017)

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In Memory of William M. Gray[3]

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

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ATLANTIC BASIN SEASONAL HURRICANE FORECAST FOR 2017

Forecast Parameter and 1981-2010 Median (in parentheses)	Issue Date 6 April 2017
Named Storms (NS) (12.0)	11
Named Storm Days (NSD) (60.1)	50
Hurricanes (H) (6.5)	4
Hurricane Days (HD) (21.3)	16
Major Hurricanes (MH) (2.0)	2
Major Hurricane Days (MHD) (3.9)	4
Accumulated Cyclone Energy (ACE) (92)	75
Net Tropical Cyclone Activity (NTC) (103%)	85

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

1) Entire U.S. coastline - 42% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 24% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 24% (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) 34% (average for last century is 42%)

ABSTRACT

Information obtained through March 2017 indicates that the 2017 Atlantic hurricane season will have activity slightly below the median 1981-2010 season. We estimate that 2017 will have 4 hurricanes (median is 6.5), 11 named storms (median is 12.0), 50 named storm days (median is 60.1), 16 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 80 percent of the long-period average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2017 to be approximately 80 percent of their long-term averages.

This forecast is based on an extended-range early April statistical prediction scheme that was developed using 29 years of past data. Analog predictors are also utilized. There is the potential for shear-enhancing El Niño conditions to develop over the next several months. The tropical Atlantic has cooled over the past month, and the far North Atlantic is currently colder than normal. 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 April. 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 April 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

These seasonal forecasts were developed by the late Dr. William Gray, who was lead author on these predictions for over 20 years and continued as a co-author until his death last year. In addition to pioneering seasonal Atlantic hurricane prediction, he conducted groundbreaking research in a wide variety of other topics including hurricane genesis, hurricane structure and cumulus convection. His investments in both time and energy to these forecasts cannot be acknowledged enough.

We are grateful for support from Interstate Restoration and Ironshore Insurance 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 have also benefited from meteorological discussions with Carl Schreck, Brian McNoldy, Art Douglas, Ray Zehr, Mark DeMaria, Todd Kimberlain, Paul Roundy, Jason Dunion and Amato Evan over the past few years.

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 34th 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 April 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 April Forecast Methodology

2.1 April Statistical Forecast Scheme

Our current April statistical forecast model was built over the period from 1982-2010 to incorporate the most recent and reliable data that is available. It uses a total of four predictors. The new Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) has been completed from 1979-2010, and the CFS model's analysis is available from 2011-present to continue this dataset in realtime. The NOAA Optimum Interpolation

(OI) SST (Reynolds et al. 2002) is available from 1982-present. This new model showed significant skill in predicting levels of Accumulated Cyclone Energy (ACE) over the 1982-2010 developmental period. The model correlates with ACE at 0.60 from 1982-2016.

Table 1 displays ACE hindcasts for 1982-2010 along with real-time forecast values for 2011-2016 using the current statistical scheme, while Figure 1 displays observations versus ACE hindcasts.

We have correctly predicted by early April above- or below-average seasons in 28 out of 35 hindcast years (80%). Our predictions have had a smaller error than climatology in 24 out of 35 years (69%). Our average hindcast error is 41 ACE units, compared with 52 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 90% 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 system 4 has significant forecast skill for SSTs across the various Nino regions for September from a 1 March forecast date. We use the ECMWF ensemble mean prediction for September Nino 3 SSTs. Table 3 displays the 2017 observed values for each of the four predictors in the new statistical forecast scheme. Table 4 displays the statistical model output for the 2017 hurricane season. Three of the four predictors are unfavorable for Atlantic hurricane activity.

Table 1: Observed versus early April hindcast ACE for 1982-2010 using our current forecast scheme as well as the statistical model's real-time output for 2011-2016. 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. The hindcast went the right way with regards to an above- or below-average season in 28 out of 35 years (80%), while hindcast improvement over climatology occurred in 24 out of 35 years (69%).

Year	Observed ACE	Hindcast ACE	Observed minus Hindcast	Observed minus Climatology	Hindcast improvement over Climatology
1982	32	86	-55	-60	6
1983	17	20	-2	-75	72
1984	84	**127**	-43	-8	**-35**
1985	88	61	27	-4	**-23**
1986	36	32	4	-56	52
1987	34	55	-21	-58	37
1988	103	127	-24	11	**-13**
1989	135	93	42	43	1
1990	97	**81**	16	5	**-11**
1991	36	80	-44	-56	12
1992	76	25	51	-16	**-36**
1993	39	48	-9	-53	44
1994	32	63	-31	-60	29
1995	227	157	71	135	65
1996	166	170	-4	74	71
1997	41	73	-32	-51	19
1998	182	157	25	90	65
1999	177	128	49	85	36
2000	119	141	-22	27	6
2001	110	100	10	18	8
2002	67	**111**	-43	-25	**-19**
2003	176	130	46	84	38
2004	227	104	123	135	12
2005	250	188	62	158	96
2006	79	**121**	-42	-13	**-29**
2007	74	**132**	-58	-18	**-40**
2008	146	182	-36	54	17
2009	53	68	-15	-39	24
2010	163	209	-46	71	25
2011	126	185	-59	34	**-25**
2012	133	**43**	90	41	**-49**
2013	36	**193**	-157	-56	**-101**
2014	67	56	11	-25	14
2015	62	35	27	-29	2
2016	134	96	38	42	4
Average	**103**	**105**	**41**	**52**	**+11**

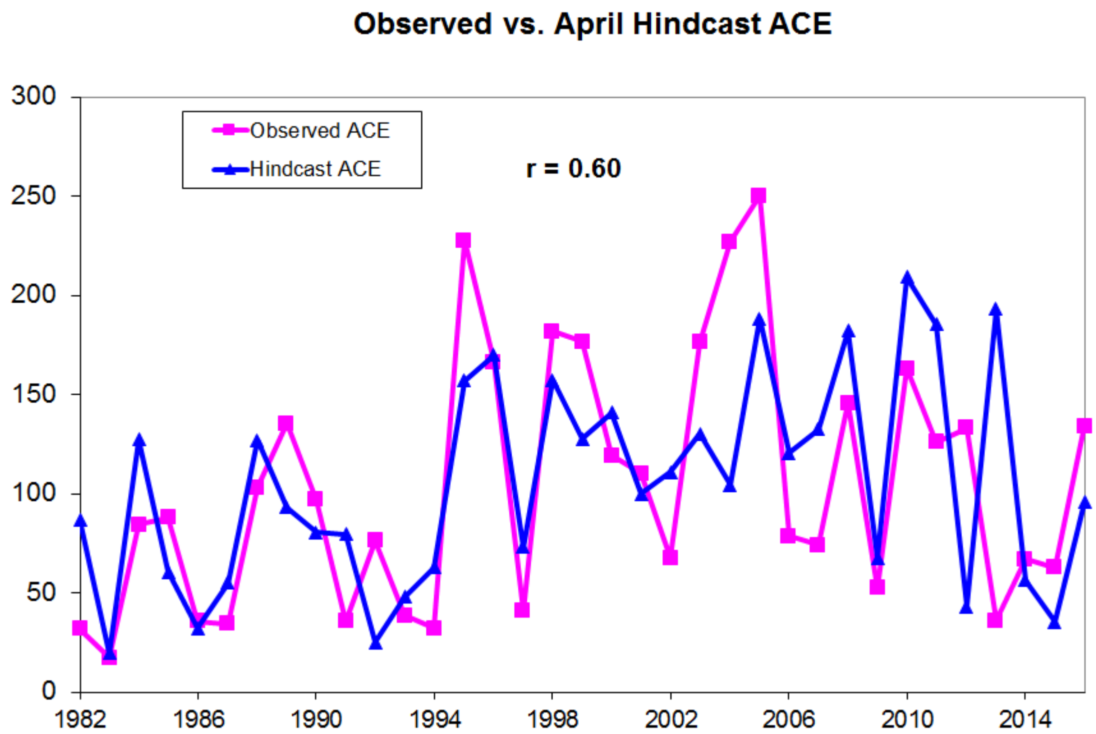


Figure 1: Observed versus early April hindcast values of ACE for 1982-2010 along with real-time forecast values for 2011-2016.

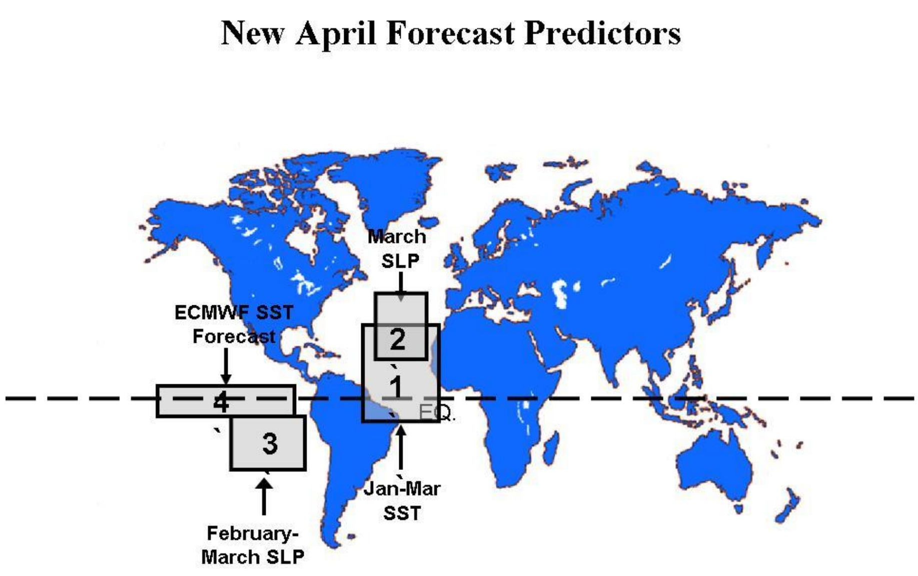


Figure 2: Location of predictors for our early April extended-range statistical prediction for the 2017 hurricane season.

Table 2: Linear correlation between each 1 April predictor and ACE over the period from 1982-2010.

Predictor	Correlation w/ ACE
1) January-March Atlantic SST (5°S-35°N, 10-40°W) (+)	0.56
2) March SLP (20-40°N, 20-35°W) (-)	-0.42
3) February-March SLP (5-20°S, 85-120°W) (+)	0.33
4) ECMWF 1 March SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.42

Table 3: Listing of 1 April 2017 predictors for the 2017 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity.

Predictor	2017 Forecast Value	Impact on 2017 TC Activity
1) Jan-Mar Atlantic SST (5°S-35°N, 10-40°W) (+)	+0.5 SD	Enhance
2) Mar SLP (20-40°N, 20-35°W) (-)	+0.8 SD	Decrease
3) Feb-Mar SLP (5-20°S, 85-120°W) (+)	-0.2 SD	Slightly Decrease
4) ECMWF 1 Mar SST Forecast for Sep Nino 3 (5°S-5°N, 90-150°W) (-)	+1.4 SD	Decrease

Table 4: Statistical model output for the 2017 Atlantic hurricane season, along with the final adjusted forecast.

Forecast Parameter and 1981-2010 Median (in parentheses)	Statistical Forecast	Final Forecast
Named Storms (12.0)	9.5	11
Named Storm Days (60.1)	44.0	50
Hurricanes (6.5)	5.2	4
Hurricane Days (21.3)	18.5	16
Major Hurricanes (2.0)	1.9	2
Major Hurricane Days (3.9)	4.0	4
Accumulated Cyclone Energy Index (92)	75	75
Net Tropical Cyclone Activity (103%)	85	85

2.2 Physical Associations among Predictors Listed in Table 2

The locations and brief descriptions of the predictors for our early April statistical forecast are now discussed. It should be noted that all predictors correlate with physical features during August through October that are known to be favorable for elevated levels of hurricane activity. These factors are all generally related to August-October vertical wind shear in the Atlantic Main Development Region (MDR) from 10-20°N, 70-20°W as shown in Figure 3.

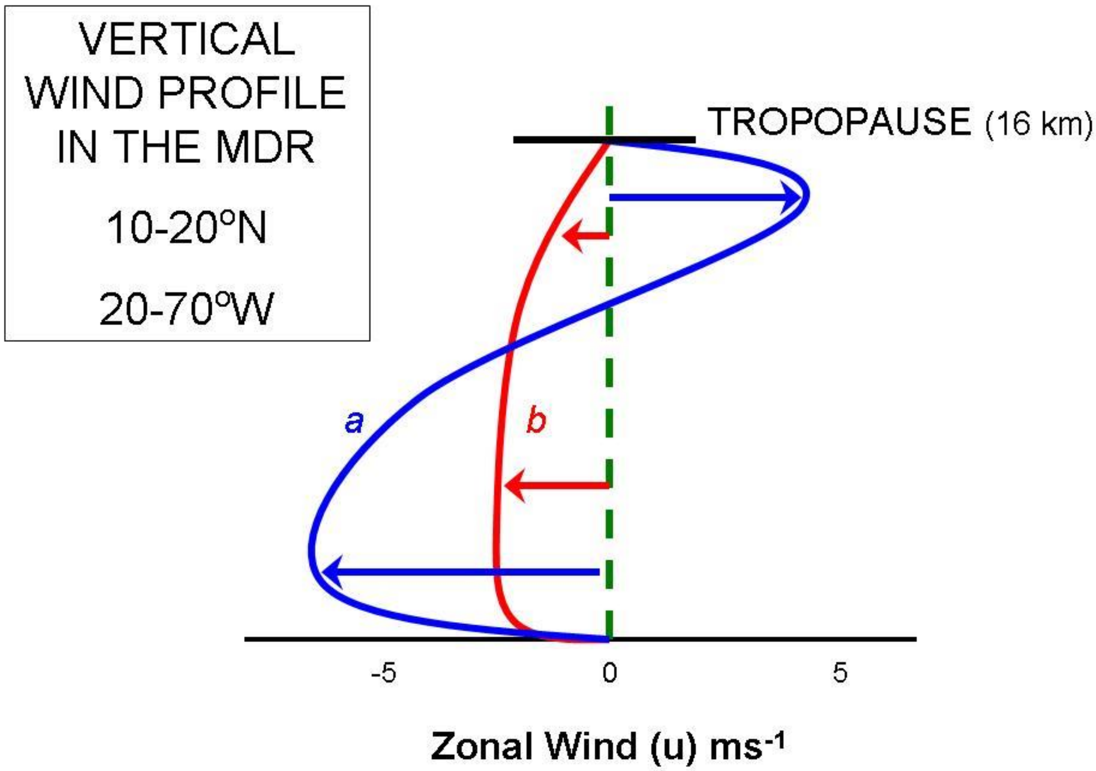


Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of vertical wind shear.

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 (SLP), 200 mb zonal wind, and 850 mb zonal wind, respectively. In general, higher values of SSTs, lower values of SLP, 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, SLP and 850 mb zonal wind correlations are displayed using the Climate Forecast System Reanalysis (CFSR), while 200 mb zonal wind correlations are displayed using the NCEP/NCAR Reanalysis, as there are questions about the quality of the upper-level wind reanalysis during the 1980s in the CFSR.

Predictor 1. January-March SST in the Tropical and Subtropical Eastern Atlantic (+)

(5°S-35°N, 40-10°W)

Warmer-than-normal SSTs in the tropical and subtropical Atlantic during the January-March time period are associated with a weaker-than-normal subtropical high and reduced trade wind strength during the boreal spring (Knaff 1997). Positive SSTs in January-March 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.

<u>Predictor 2. March SLP in the Subtropical Atlantic (-)</u>

(20-40°N, 35-20°W)

Our April statistical scheme in the late 1990s used a similar predictor when evaluating the strength of the March Atlantic sub-tropical ridge (Azores High). If the pressure in this area is higher than normal, it correlates strongly with increased Atlantic trade winds. These stronger trades enhance ocean mixing and upwelling, driving cooler tropical Atlantic SSTs. These cooler SSTs are associated with higher-than-normal sea level pressures which can create a self-enhancing feedback that relates to higher pressure, stronger trades and cooler SSTs during the hurricane season (Figure 5) (Knaff 1998). All three of these factors are associated with inactive hurricane seasons.

<u>Predictor 3. February-March SLP in the southeastern tropical Pacific (+)</u>

(5-20°S, 120-85°W)

High pressure in the southeastern tropical Pacific during the months of February-March correlates strongly with a positive Southern Oscillation Index and strong trades blowing across the eastern tropical Pacific. Strong trade winds help prevent eastward propagating Kelvin waves from transporting warmth from the western Pacific warm pool region and triggering El Niño conditions. During the August-October period, positive values of this predictor are associated with weaker trades and lower sea level pressures in the tropical Atlantic and relatively cool SST anomalies in the eastern Pacific (typical of La Niña conditions) (Figure 6). The combination of these features is typically associated with more active hurricane seasons.

<u>Predictor 4. ECMWF 1 March SST Forecast for September Nino 3 (-)</u>

(5°S -5°N, 150-90°W)

The ECMWF seasonal forecast system 4 has shown skill at being able to predict SST anomalies associated with ENSO several months into the future (Stockdale et al. 2011). 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 March forecast date correlates with observations at 0.63, which is impressive considering that this forecast goes through the springtime predictability barrier, where fluctuations in ENSO lead to greatly reduced forecast skill. 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 7).

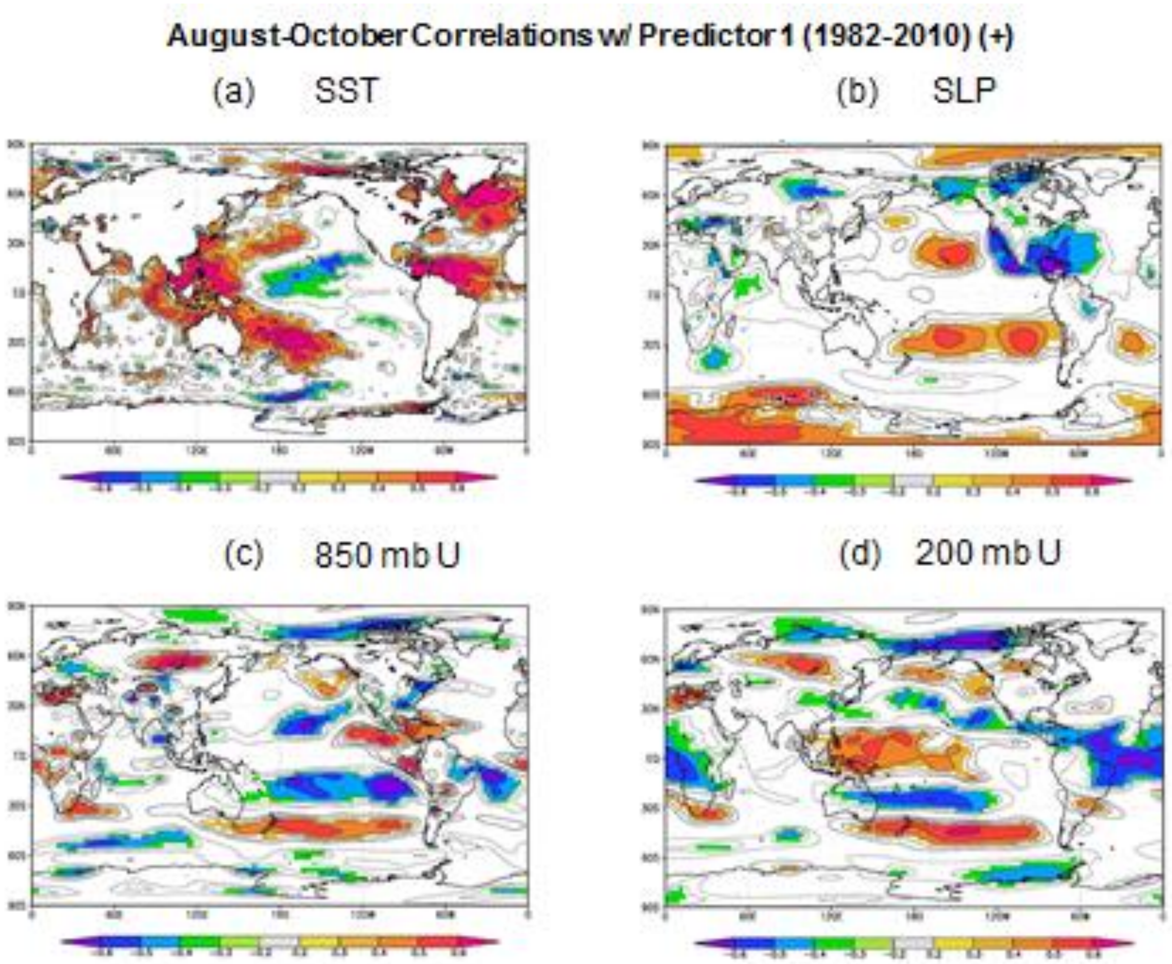


Figure 4: Linear correlations between January-March SST in the tropical and subtropical Atlantic (Predictor 1) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).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

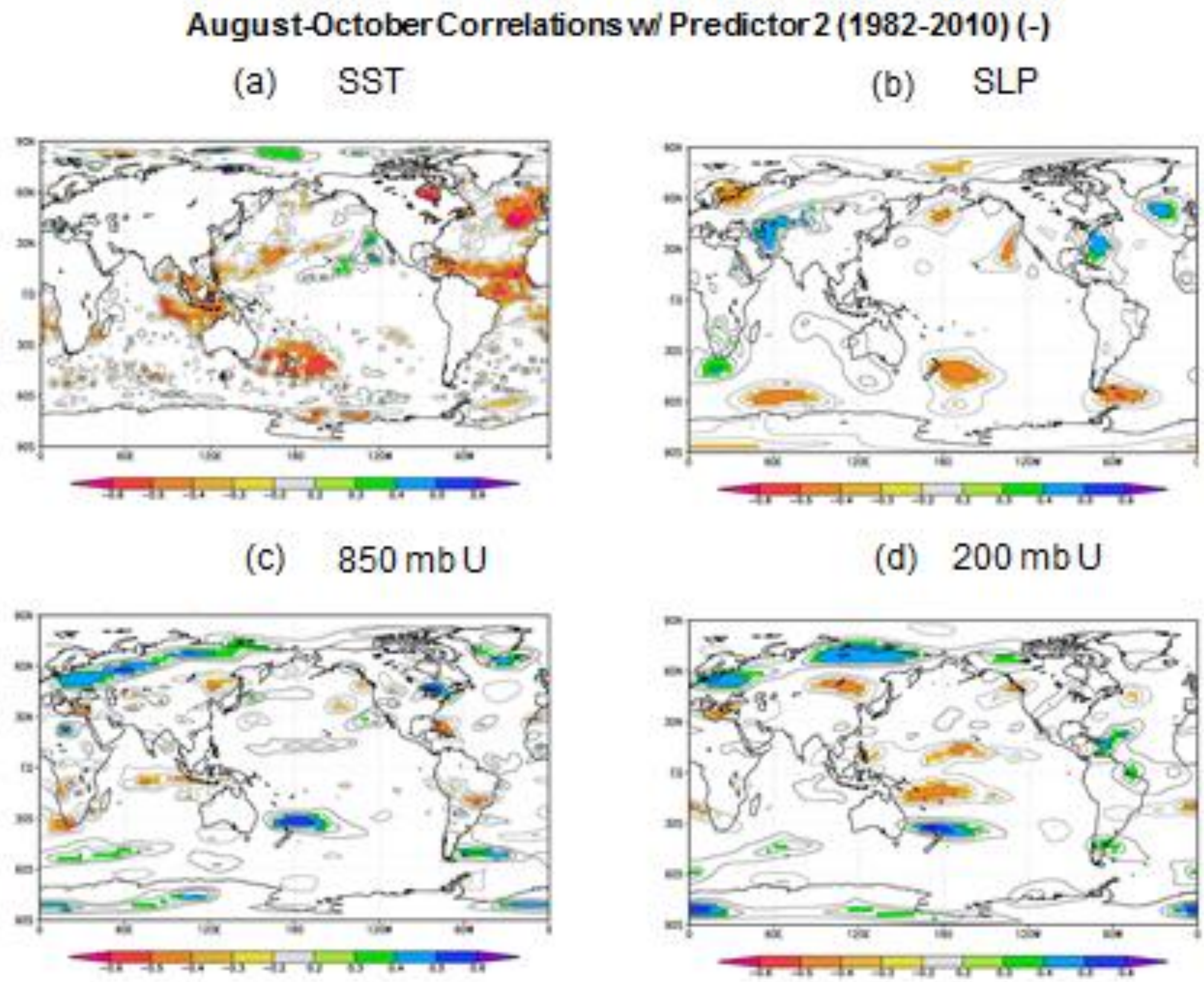


Figure 5: Linear correlations between March SLP in the subtropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor's primary impact during the hurricane season appears to be with MDR-averaged SST. **The correlation scale has been reversed (sign changed) to allow for easy comparison of correlations for all four predictors.**

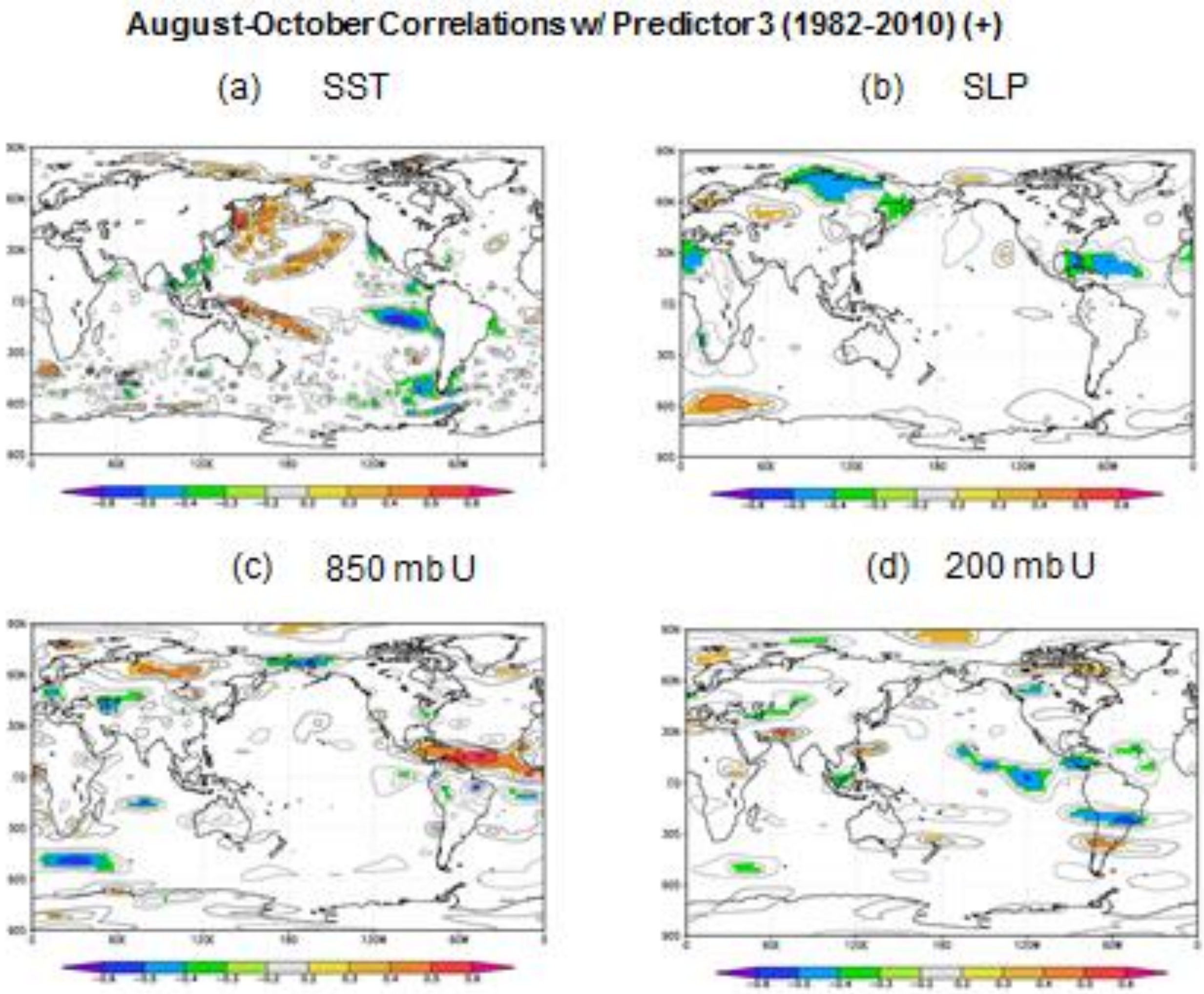


Figure 6: Linear correlations between February-March SLP in the southern tropical Pacific (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor's primary impacts appear to be on sea level pressure and trade wind strength across the tropical Atlantic.

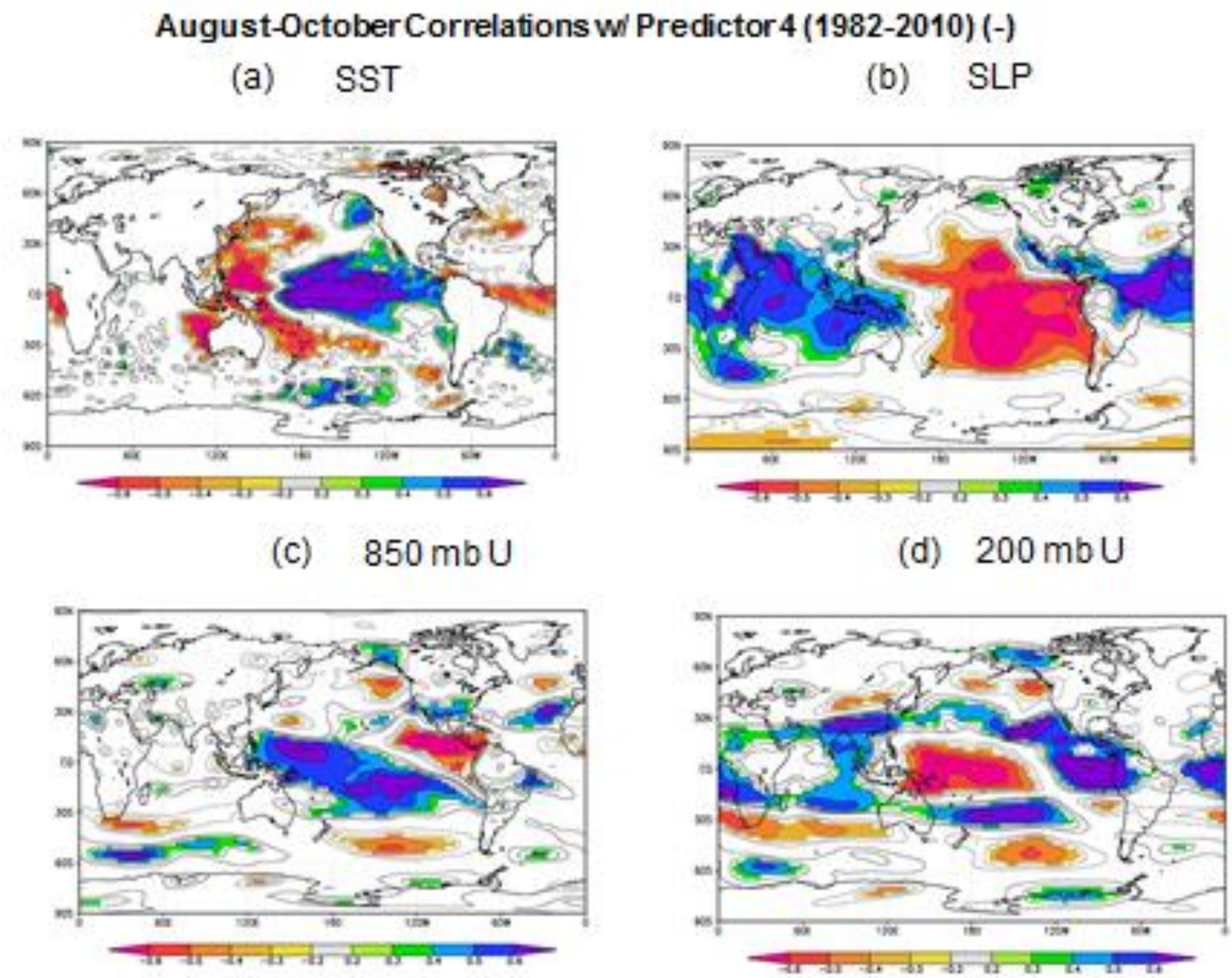


Figure 7: Linear correlations between a 1 March ECMWF SST forecast for September Nino 3 (Predictor 4) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d). The predictor correlates very strongly with ENSO as well as vertical shear in the Caribbean. **The correlation scale has been reversed (sign changed) 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. Uncertainty with the April outlook is quite large, given the uncertainty in the state of both ENSO as well as the state of the Atlantic basin SST configuration.

Table 5 provides our early April forecast, 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. Note the rather large uncertainty ranges at this extended lead time. Large changes in the atmosphere-ocean system frequently occur during the spring months and can lead to significant alterations to the seasonal forecast as the peak of the hurricane season approaches.

Table 5: Model hindcast error and our 2017 hurricane forecast. Uncertainty ranges are given in one standard deviation (SD) increments.

Parameter	Hindcast Error (SD)	2017 Forecast	Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range)
Named Storms (NS)	3.4	11	7.6 – 14.4
Named Storm Days (NSD)	21.5	50	28.5 – 71.5
Hurricanes (H)	2.4	4	1.6 – 6.4
Hurricane Days (HD)	12.7	16	3.3 – 28.7
Major Hurricanes (MH)	1.5	2	0.5 - 3.5
Major Hurricane Days (MHD)	5.5	4	0 – 9.5
Accumulated Cyclone Energy (ACE)	53	75	22 – 128
Net Tropical Cyclone (NTC) Activity	50	85	35 - 135

4 Analog-Based Predictors for 2017 Hurricane Activity

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2017. These years also provide useful clues as to likely trends in activity that the forthcoming 2017 hurricane season may bring. For this early April 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 February-March 2017 conditions as well as projected August-October 2017 conditions. Table 6 lists our analog selections.

We selected prior hurricane seasons since 1950 which had similar atmospheric-oceanic conditions to those currently being experienced and those that we expect to see this summer and fall. We searched for years that were generally characterized by neutral to weak La Niña conditions the previous year with a transition to weak or moderate El Niño conditions during the current year. We selected a variety of tropical and North Atlantic SST anomaly configurations due to the large uncertainty as to what the Atlantic will look like this summer and fall. We anticipate that the 2017 hurricane season will have about as much activity as the average of our five analog years. We believe that this season should experience slightly below-average activity.

Table 6: Best analog years for 2017 with the associated hurricane activity listed for each year.

Year	NS	NSD	H	HD	MH	MHD	ACE	NTC
1957	8	41.25	3	21.00	2	3.75	79	78
1965	6	39.50	4	27.25	1	7.50	84	86
1972	7	30.75	3	6.25	0	0.00	36	35
1976	10	49.50	6	25.50	2	1.00	84	86
2002	12	57.00	4	10.75	2	3.00	67	83
Average	8.6	43.6	4.0	18.2	1.4	3.1	70	74
2017 Forecast	**11**	**50**	**4**	**16**	**2**	**4**	**75**	**85**

5 ENSO

Weak La Niña conditions occurred over the tropical Pacific during this past winter and have since transitioned to neutral ENSO conditions. The Nino 3.4 index (5°S-5°N, 170-120°W) rapidly decreased from 1.5°C in early April to below normal SSTs by the middle of June. The Nino 3.4 index hovered around -0.5°C for several months during the summer and fall of 2016. The -0.5°C threshold in the Nino 3.4 region is generally considered to be the threshold for La Niña conditions. SSTs have been slowly increasing since December and are now slightly above normal.

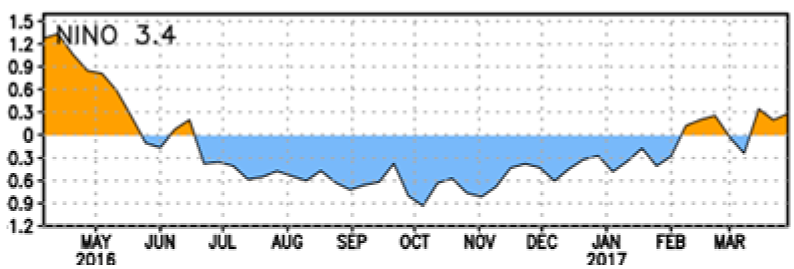


Figure 8: Nino 3.4 SST anomalies from April 2016 through March 2017. Figure courtesy of Climate Prediction Center.

Upper-ocean heat content anomalies in the eastern and central tropical Pacific have increased considerably over the past several months and reached above-normal levels during the middle of January. Since that time, upper ocean heat content anomalies have generally continued to slowly increase, although they have decreased slightly over the past two weeks. Increasing upper ocean heat content anomalies are often a sign of a developing El Niño.

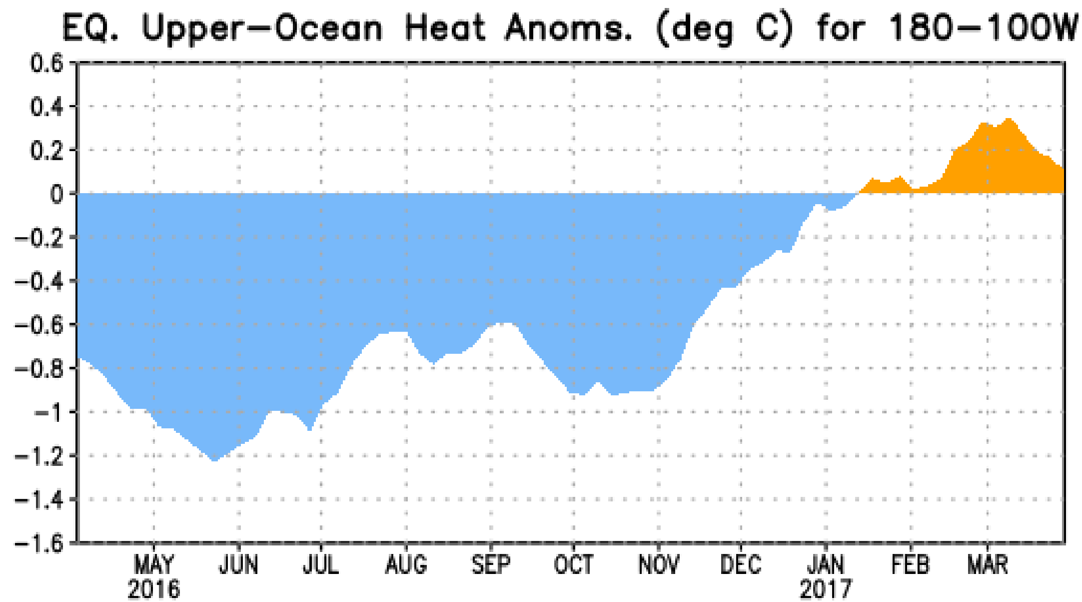


Figure 9: Central and eastern tropical Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Upper ocean heat content anomalies have generally been on an increasing trend since November 2016.

SSTs are near normal across portions of the central and eastern Pacific, with very warm anomalies in the far eastern tropical Pacific off of the west coast of South America. Current SST anomalies in the Nino 1+2 region (0-10°S, 90-80°W) are some of the warmest ever observed. These warm SST anomalies off of the west coast of South America may be a harbinger of a developing El Niño event (Figure 10).

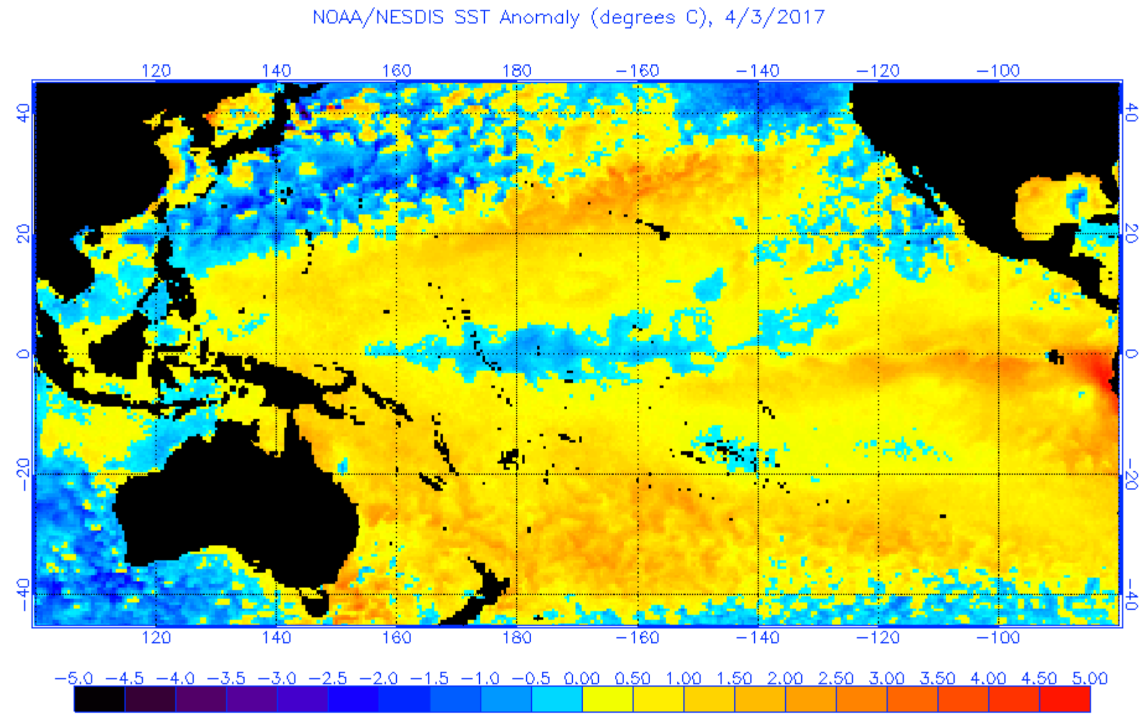


Figure 10: Current SST anomalies across the tropical and subtropical Pacific. Note the very warm SST anomalies that currently exist off of the west coast of South America.

Table 7 displays January and March SST anomalies for several Nino regions. Anomalies have generally trended upward over the past couple of months, with the most marked increase along the west coast of South America. SST anomalies in the Nino 1+2 region have only exceeded +2.0°C in March (since 1950) on two other occasions: 1983 and 1998. Both of these March values occurred while coming out of strong El Niño events. This event is different, however, as we have just come out of a weak La Niña event. This warming is also unusual in its magnitude, especially given that SST anomalies in the central tropical Pacific are slightly below normal.

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

Region	January SST Anomaly (°C)	March SST Anomaly (°C)	March – January SST Anomaly (°C)
Nino 1+2	1.2	2.0	+0.8
Nino 3	0.0	0.5	+0.5
Nino 3.4	-0.3	0.1	+0.4
Nino 4	-0.1	-0.1	0.0

In general, we had relatively weak Kelvin wave activity across the tropical Pacific through most of last summer and fall (Figure 11). Towards the end of last year, a downwelling Kelvin wave began to track across the tropical Pacific, contributing to significant warming in the eastern tropical Pacific around the middle of January. Since that time, trade winds across the eastern tropical Pacific have weakened considerably, contributing to sustenance of these warm anomalies (Figure 12). These warm anomalies have now slowly progressed westward, in a manner similar to what was observed during several pre-1980 El Niños (Rasmusson and Carpenter 1982).

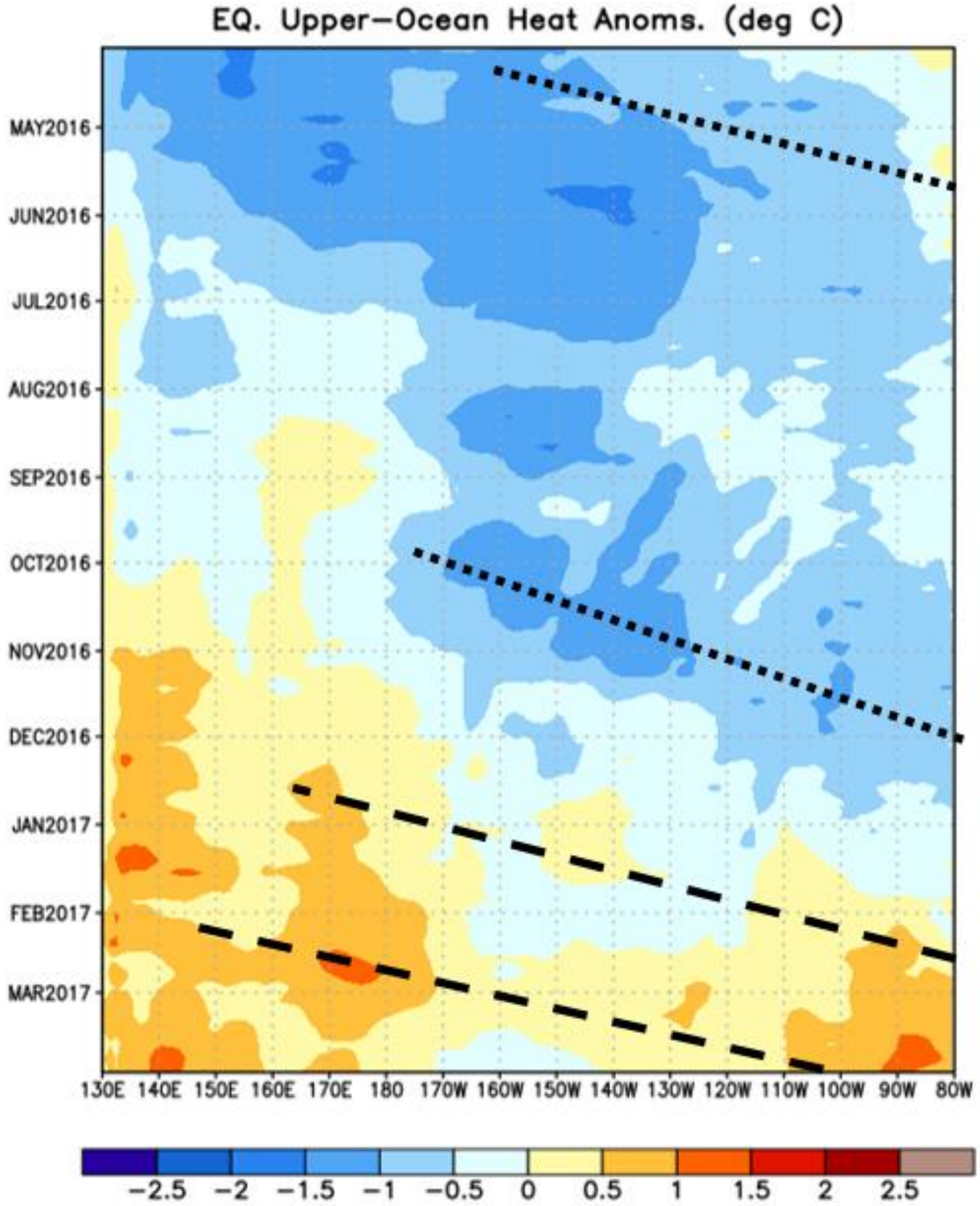
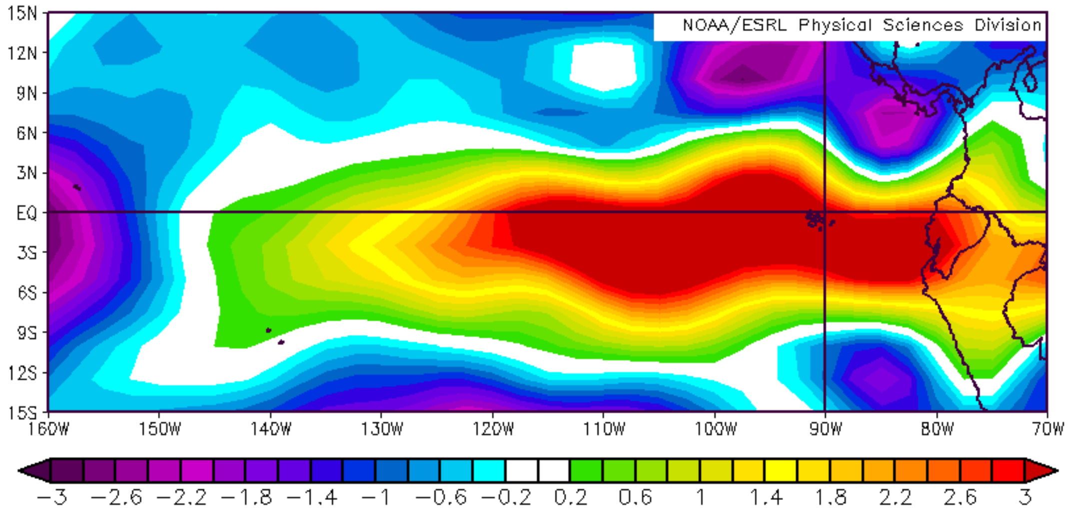


Figure 11: Upper-ocean heat content anomalies in the tropical Pacific since April 2016. Dashed lines indicate downwelling Kelvin waves, while dotted lines indicate upwelling Kelvin waves. Downwelling Kelvin waves result in upper-ocean heat content increases, while upwelling Kelvin waves recent in upper-ocean heat content decreases.



February-March 2017 850 mb Wind Anomalies

Figure 12: February through March 2017 850 mb zonal wind anomalies across the tropical eastern and central Pacific. The trade winds have been much weaker than normal across the eastern part of the basin.

The current potential development of El Niño is quite different from what has been observed with El Niños since 1980. Typically, El Niños in the recent past have developed with westerly wind bursts in the central Pacific that have transported warm water from the western and central Pacific to the eastern Pacific. Following the downwelling Kelvin wave and associated warming in the eastern tropical Pacific in December-January, the trade winds in the eastern tropical Pacific have remained weak, reinforcing these warm anomalies (Figure 13). The type of El Niño development that we are currently potentially witnessing with warming developing first in the eastern tropical Pacific and progressing westward may have been more common prior to 1980, as noted in a classic ENSO paper published by two NOAA scientists in 1982 (Rasmusson and Carpenter 1982) (Figure 14).

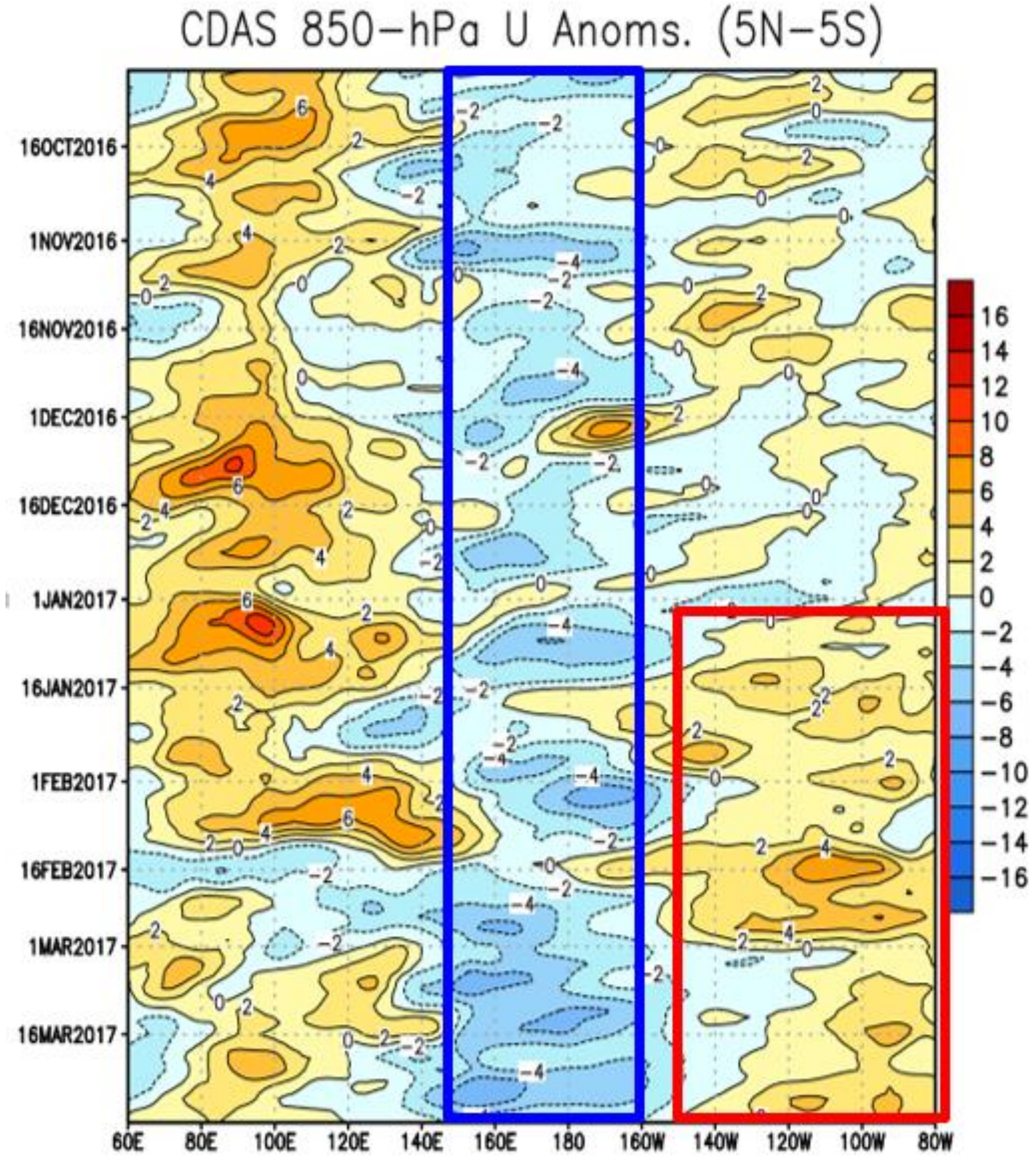


Figure 13: Low-level wind anomalies across the tropical Pacific since October 2016.

Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño

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ABSTRACT

Surface marine observations, satellite data, and station observations of surface pressure and precipitation are used to describe the evolution of sea surface temperature (SST) anomalies, surface wind fields, and precipitation anomaly patterns during major warm episodes in the eastern and central tropical Pacific. The sequence of events is described in terms of composite SST and wind fields (30°N–30°S) for six warm episodes since 1949, and time series and cross-spectral analyses of mean monthly data along six shipping lanes which cross the equator between the South American coast and 170°W.

During the months preceding a warm episode, the equatorial easterlies are stronger than normal west of the dateline. This and other coherent and strongly developed anomaly patterns over the western equatorial Pacific and South Pacific are associated with a South Pacific Convergence Zone (SPCZ) located southwest of its normal position. During October–November prior to El Niño, the equatorial easterly anomalies in the western Pacific are replaced by westerly anomalies. This change coincides with the appearance of positive SST anomalies in the vicinity of the equator near the dateline. East of the dateline (140–170°W), the wind anomalies along the equator follow a different pattern, with the diminution of the easterlies lagging rather than leading the development of positive SST anomalies near the Ecuador–Peru coast. Further south, SST's increase and the easterlies show a general decrease over most of the latitude band 10–30°S prior to the coastal warming.

Composites and cross-spectral analysis clearly show a westward migration of the eastern equatorial Pacific SST anomaly pattern from the South American coast into the central equatorial Pacific. Maximum SST anomalies typically occur around April–June along the South American coast, and near the end of the year around 170°W. This westward spread of positive SST anomalies coincides with the intensification of westerly wind anomalies along the equator and the development of anomalous northerly flow across the mean position of the Intertropical Convergence Zone (ITCZ). The southward shift of this convergence belt is accompanied by a northeastward shift of the SPCZ, resulting in a smaller wedge-shaped dry zone and enhanced precipitation in the eastern and central tropical Pacific. The surface wind anomaly field in the central equatorial Pacific is most strongly developed during August–December following the maximum SST anomalies along the Ecuador–Peru coast. During the northern winter following El Niño, the positive SST anomalies, as well as the low-level convergence and positive precipitation anomalies, are concentrated in the central equatorial Pacific. A simple calculation based on the surface divergence composite indicates that at this time enhanced large-scale vapor flux convergence in this area is comparable in magnitude to the enhanced precipitation.

The western end of a precipitation anomaly seesaw also appears in the data. Below normal precipitation is observed over Indonesia during the year of El Niño. Negative precipitation anomalies in the subtropics are associated with enhanced divergence and a weakened east Asian northeast winter monsoon in the Northern Hemisphere, and a weakened summer convergence zone east of Australia in the Southern Hemisphere.

Figure 14: Abstract of Rasmusson and Carpenter (1982) discussing El Niño development from east to west across the tropical Pacific.

One caveat with the development of El Niño would be a trade wind surge in the eastern tropical Pacific associated with a robust Madden-Julian Oscillation (MJO) event. If this were to occur, strong upwelling could occur along the South American coast, potentially inhibiting the development of El Niño. However, at this point, the latest monthly MJO forecast from the ECMWF indicates weak MJO activity for the next several weeks (Figure 15).

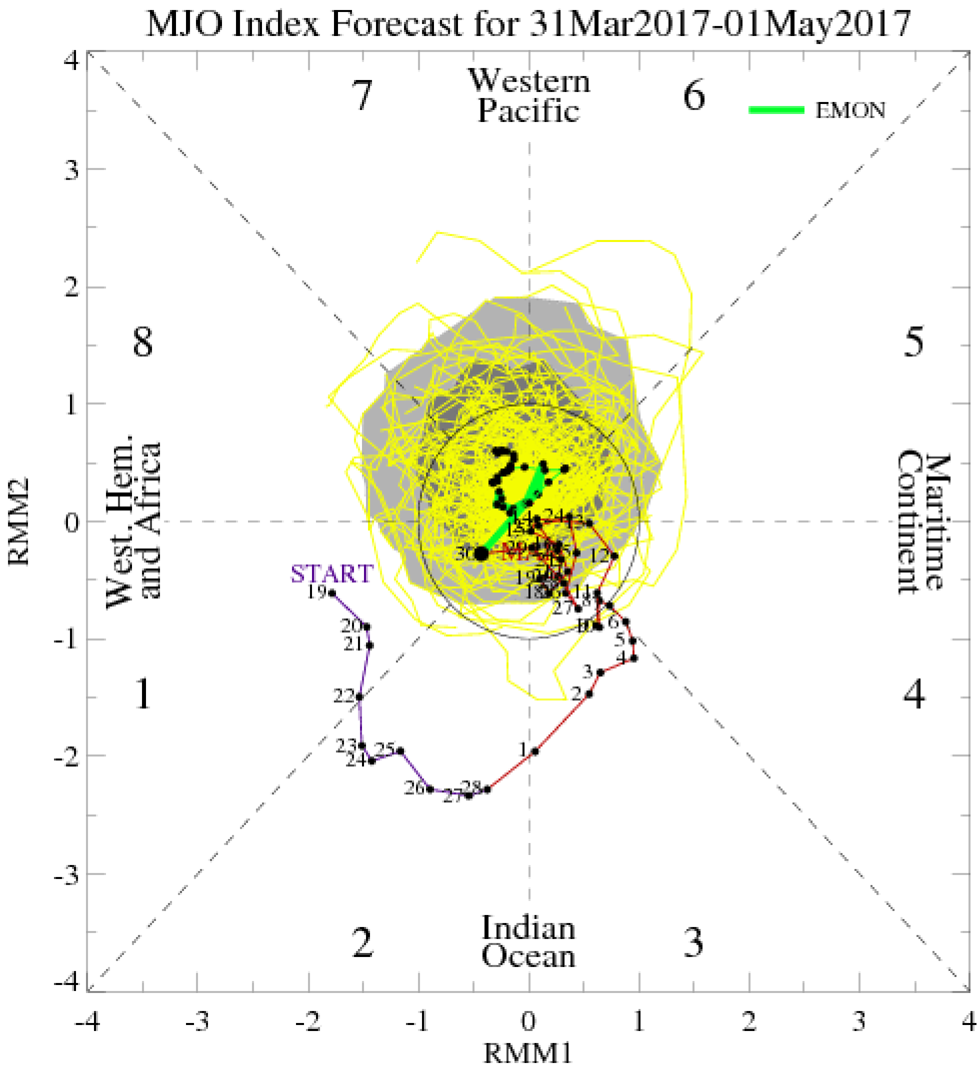

Figure 15: Monthly forecast of the MJO from the ECMWF model. The ECMWF model calls for continued weak MJO activity, as indicated by the green line being near the center of the circle.

There is obviously considerable uncertainty with the future state of El Niño. The latest plume of ENSO predictions from a large number of statistical and dynamical models shows a large spread by the peak of the Atlantic hurricane season in August-October (Figure 16). The dynamical models are generally more aggressive at calling for warming than the statistical models, with the dynamical model average calling for a ~1.0°C warm anomaly in the Nino 3.4 region by August through October, indicative of a moderate El Niño event.

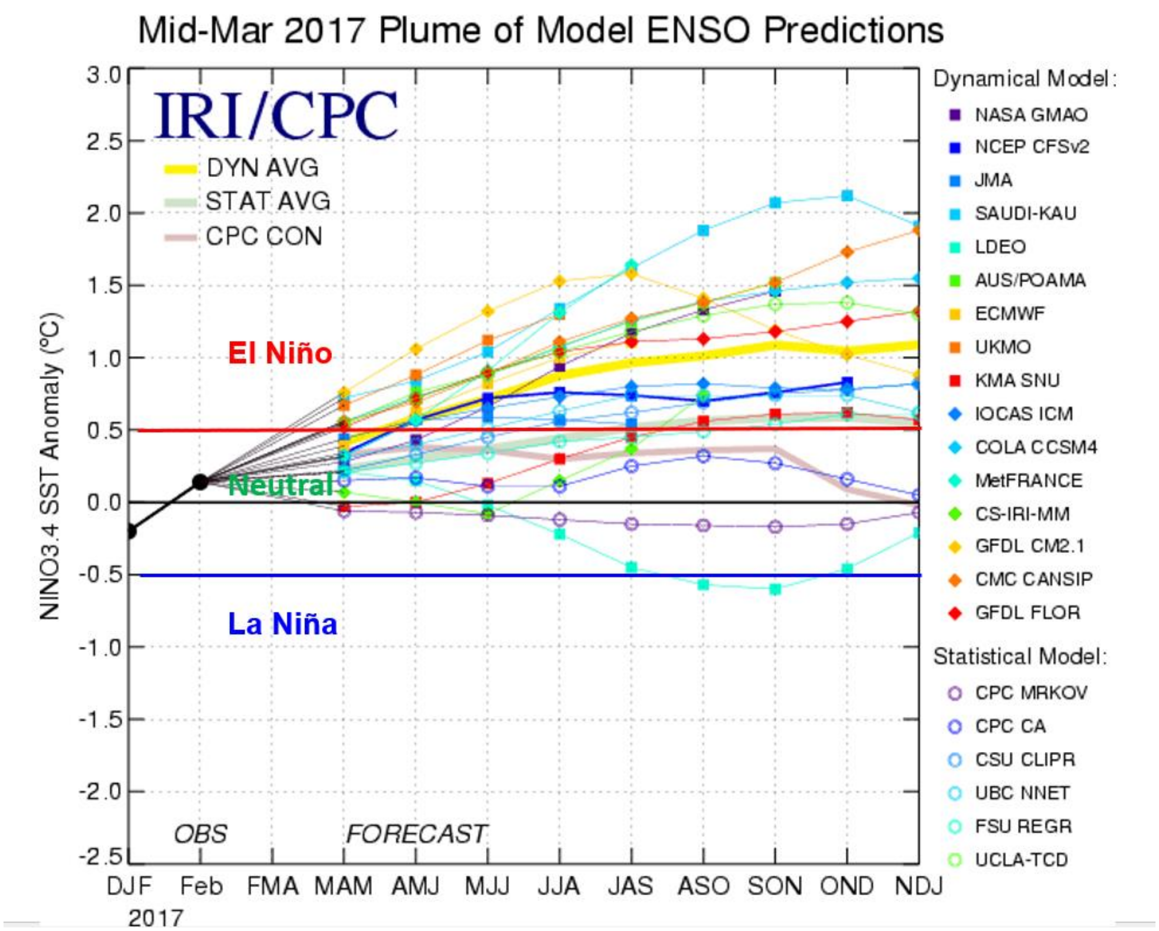

Figure 16: ENSO forecasts from various statistical and dynamical models for the Nino 3.4 SST anomaly based on March initial conditions. Figure courtesy of the International Research Institute (IRI). Most dynamical models are calling for El Niño during August-October.

We find that, in general, the European Centre for Medium-Range Weather Forecasts (ECMWF) shows the best prediction skill of any individual ENSO model. The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately +1.1°C. There is a fairly wide spread for the range of outcomes predicted by the various ensemble members, which indicates the large degree of uncertainty in future ENSO conditions (Figure 17). This is typically what would be expected with a forecast initialized in March, as predicting ENSO is generally most challenging during the Northern Hemisphere spring.

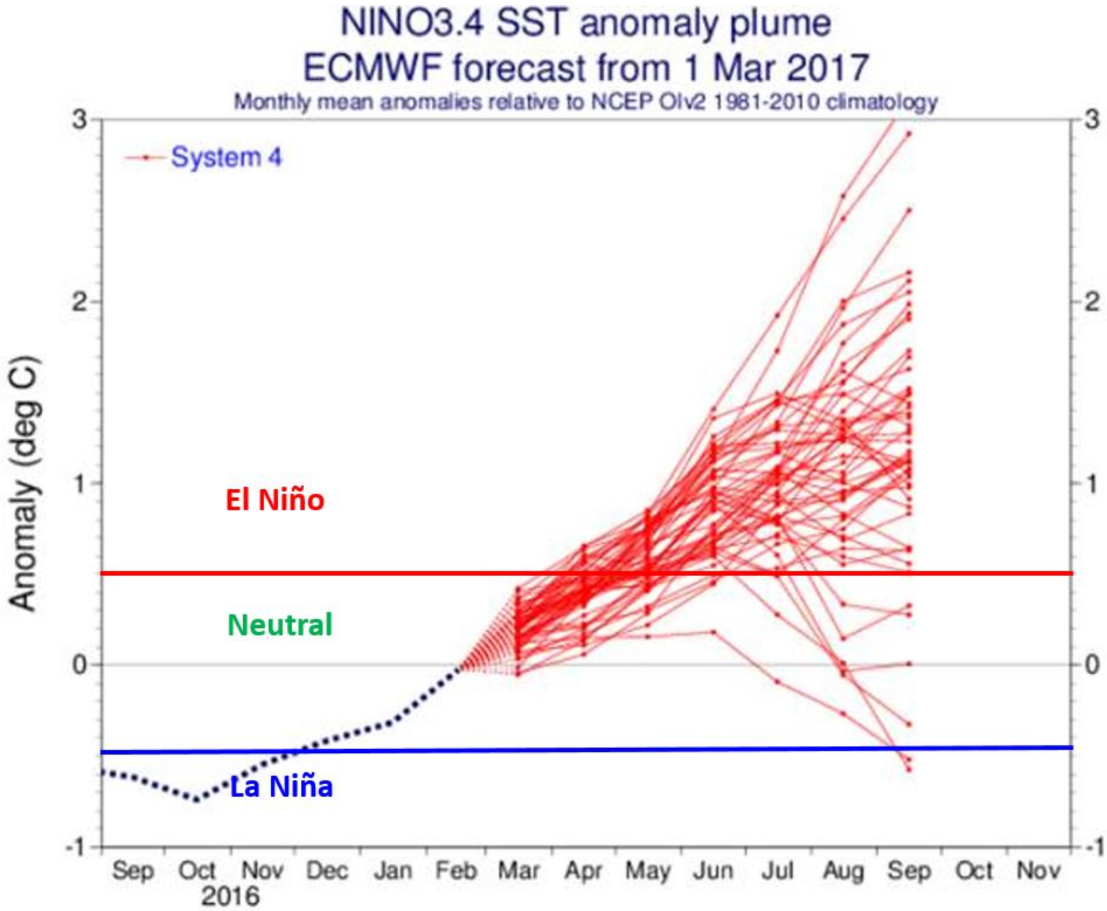

Figure 17: ECMWF ensemble model forecast for the Nino 3.4 region. Most members are calling for El Niño conditions by September, but there is large spread at this long lead time.

A recent ensemble average forecast from NOAA's Climate Forecast System model (CFS) calls for borderline weak/moderate El Niño development by August-October (Figure 18), but several forecast members do keep SSTs in the neutral ENSO category.

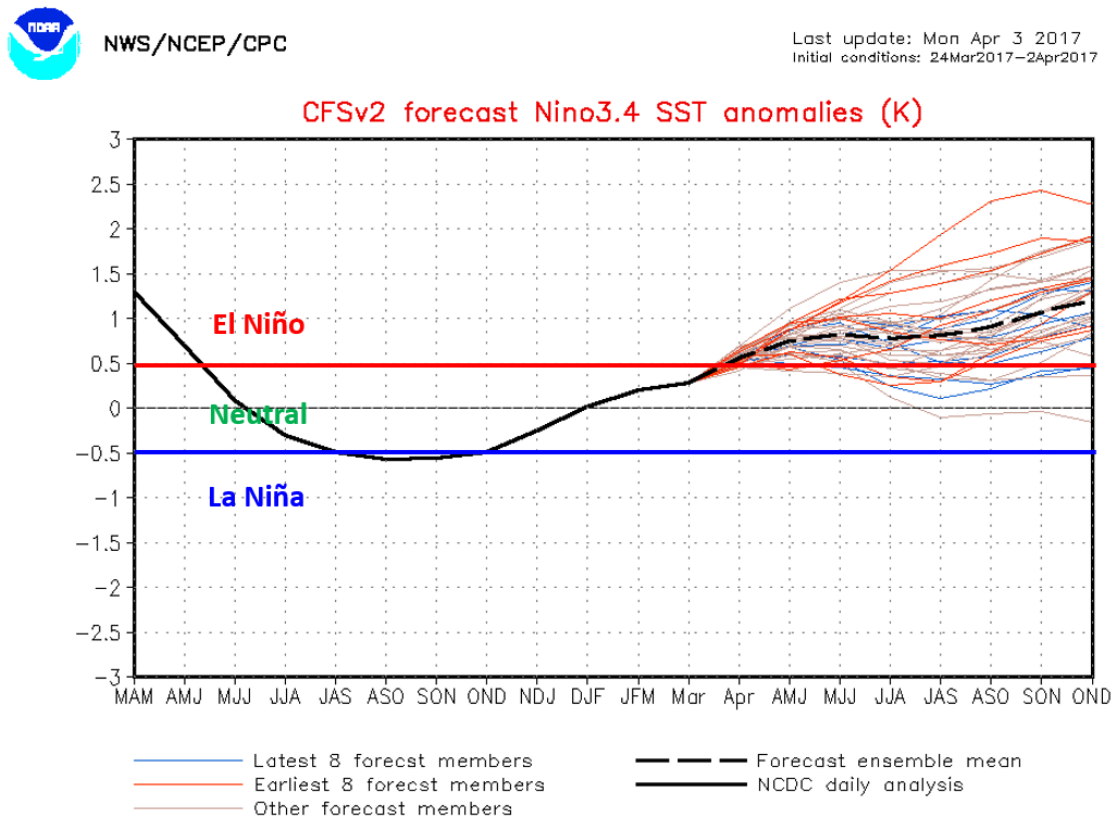

Figure 18: A recent forecast from the CFSv2 model, with the ensemble mean calling for borderline weak/moderate El Niño conditions for the late summer/early fall.

Based on the above information, our best estimate is that we will likely have weak to moderate El Niño conditions by the peak of the Atlantic hurricane season. There remains a need to closely monitor ENSO conditions over the next few months. We believe we will be somewhat more confident about ENSO conditions for the upcoming hurricane season by the time of our next forecast on June 1.

6 Current Atlantic Basin Conditions

The current SST pattern across the North Atlantic basin is characterized by cold anomalies in the far North Atlantic, relatively cool anomalies in the eastern tropical Atlantic and warm anomalies off of the East Coast of the United States. This type of SST pattern is typically associated with a negative phase of the Atlantic Multidecadal Oscillation (AMO) pattern (Figure 19).

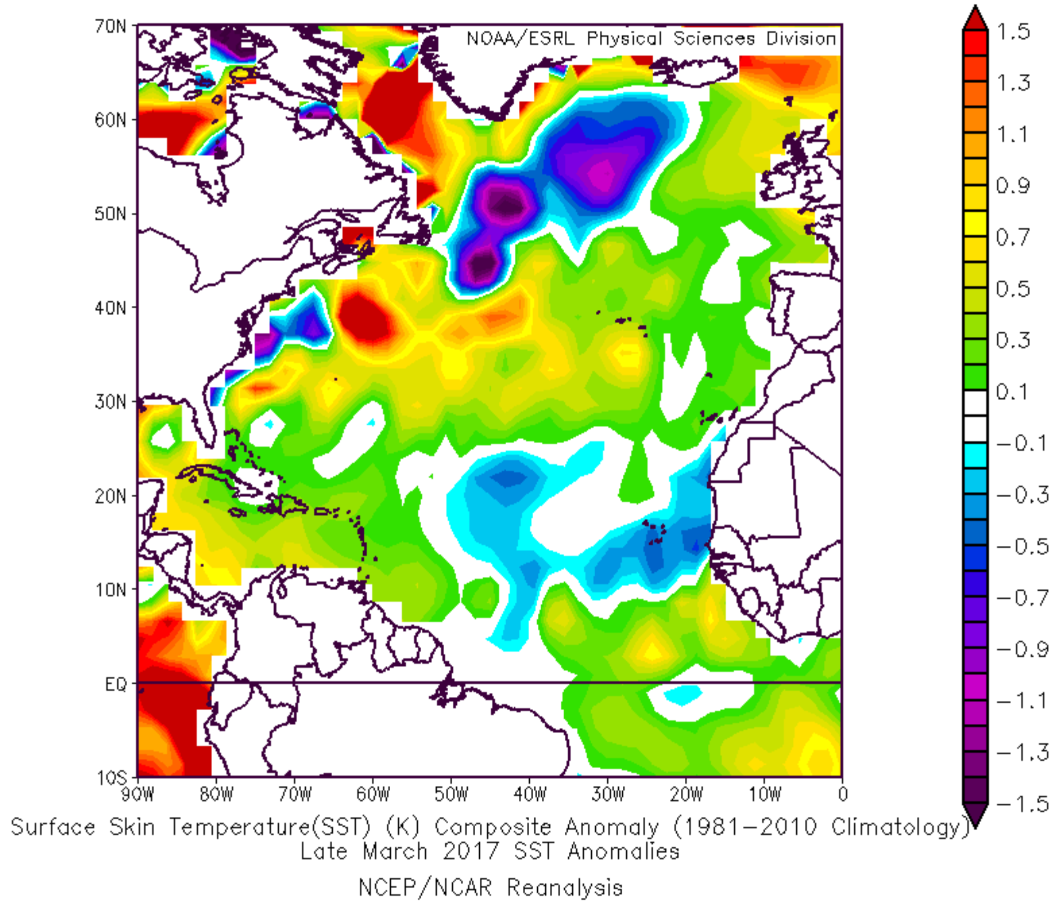

Figure 19: Late March 2017 SST anomaly pattern across the Atlantic Ocean.

There has been significant cooling across both the tropical Atlantic and far North Atlantic over the last month (Figure 20). Much of this anomalous cooling is due to a persistent positive phase of the North Atlantic Oscillation (NAO) since late last year (Figure 21). While the NAO has generally been positive since January, the anomalous cooling really ramped up in March. The trade winds have been very strong across the tropical Atlantic during March, driving increased evaporation, upwelling and associated SST cooling (Figure 22).

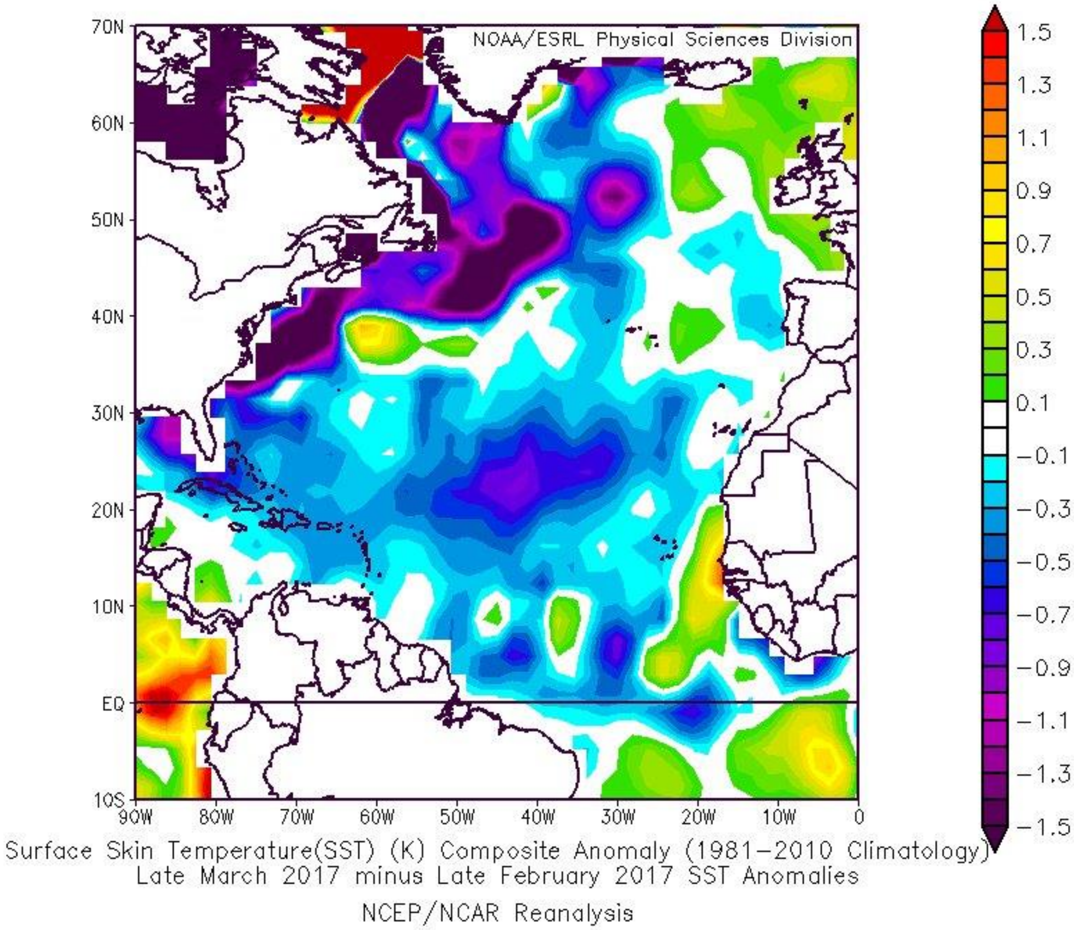

Figure 20: Late March 2017 minus late February 2017 SST anomalies. Most of the North Atlantic has undergone anomalous cooling.

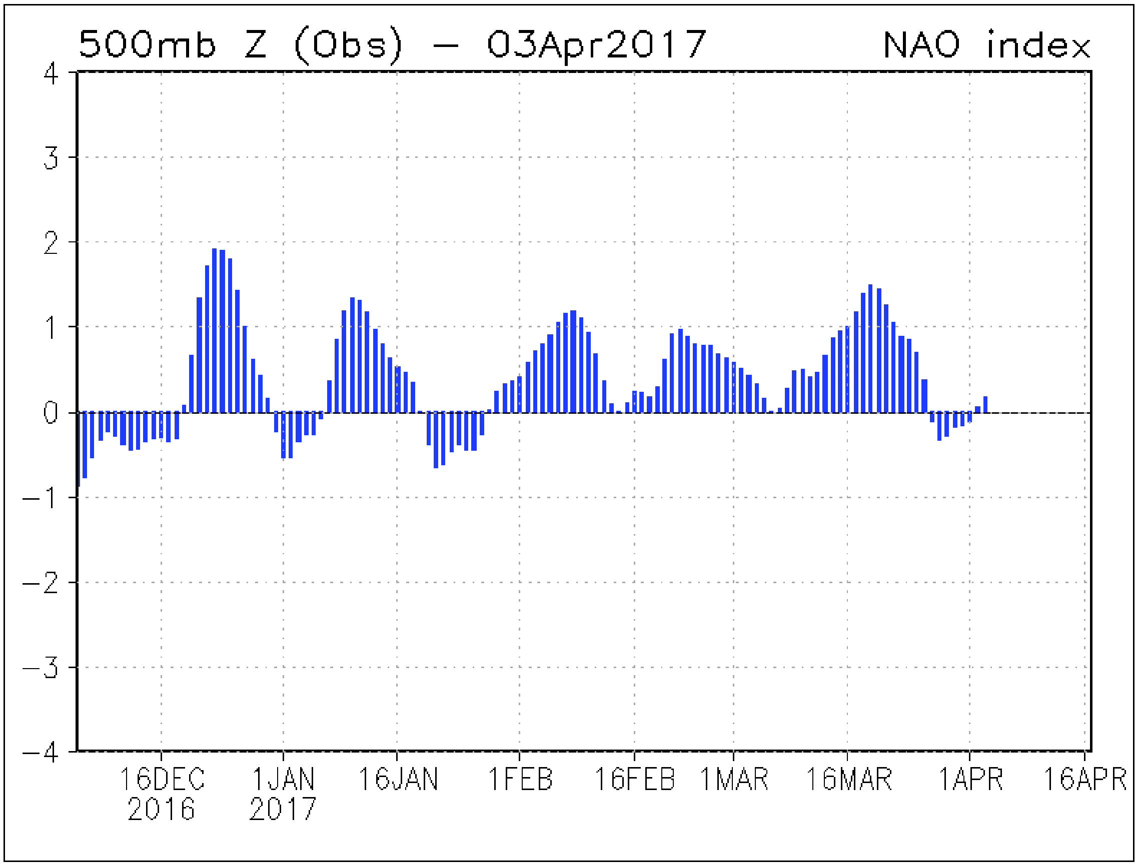

Figure 21: Observed standardized values of the daily NAO since December 2016. The NAO has generally been positive over the past several months with strong positive anomalies predominating in March.

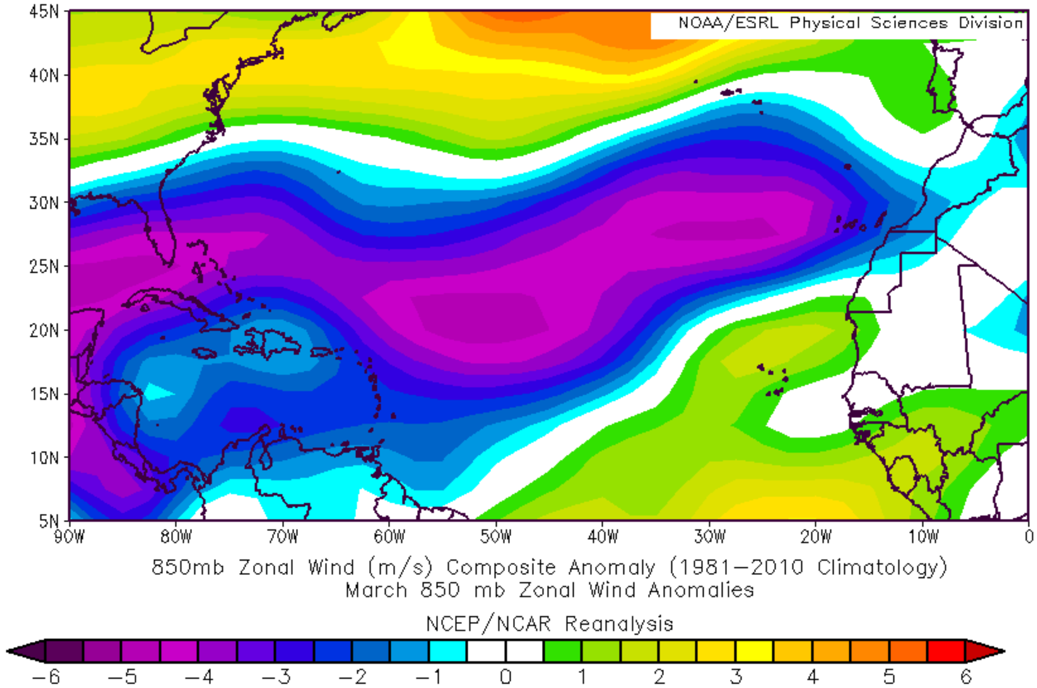

Figure 22: March low-level wind anomalies across the tropical and subtropical Atlantic. In general, easterly wind anomalies have prevailed, indicative of stronger than normal trade winds.

There remains considerable uncertainty as to whether the current anomalous SST cooling in the tropical Atlantic will persist over the next several months. In general, the current Atlantic SST pattern does not look particularly conducive for an active Atlantic hurricane season, however.

7 Adjusted 2017 Forecast

Table 8 shows our final adjusted early April forecast for the 2017 season which is a combination of our statistical scheme, our analog scheme and qualitative adjustments for other factors not explicitly contained in either of these schemes. Both our analog and statistical forecast call for a slightly below-average Atlantic hurricane season this year.

Table 8: Summary of our early April statistical forecast, our analog forecast and our adjusted final forecast for the 2017 hurricane season.

Forecast Parameter and 1981-2010 Median (in parentheses)	Statistical Scheme	Analog Scheme	Adjusted Final Forecast
Named Storms (12.0)	9.5	8.6	11
Named Storm Days (60.1)	44.0	43.6	50
Hurricanes (6.5)	5.2	4.0	4
Hurricane Days (21.3)	18.5	16.0	16
Major Hurricanes (2.0)	1.9	1.4	2
Major Hurricane Days (3.9)	4.0	3.1	4
Accumulated Cyclone Energy Index (92)	75	70	75
Net Tropical Cyclone Activity (103%)	85	74	85

8 Landfall Probabilities for 2017

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 accurately 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 1950-2000 climatological 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 landfall probabilities for the 2017 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 NTC activity in 2017 is expected to be slightly below its long-term average of 100, and therefore, landfall probabilities are slightly below their long-term average.

Please visit the Landfalling Probability Webpage for landfall probabilities for 11 U.S. coastal regions and 205 coastal and near-coastal counties from Brownsville, Texas to Eastport, Maine. The probability of each U.S. coastal state being impacted by hurricanes and major hurricanes is also included. In addition, we 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.

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 2017. 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)	69% (79%)	57% (68%)	42% (52%)	75% (84%)	92% (97%)
Gulf Coast (Regions 1-4)	48% (59%)	34% (42%)	24% (30%)	49% (60%)	74% (83%)
Florida plus East Coast (Regions 5-11)	41% (50%)	35% (44%)	24% (31%)	51% (61%)	71% (81%)
Caribbean (10-20°N, 60-88°W)	73% (82%)	47% (57%)	34% (42%)	65% (75%)	90% (96%)

9 Summary

An analysis of a variety of different atmosphere and ocean measurements (through March) which are known to have long-period statistical relationships with the upcoming season's Atlantic tropical cyclone activity indicate that 2017 should have slightly below-average activity. The big question marks with this season's predictions are whether an El Niño develops, 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.

10 Forthcoming Updated Forecasts of 2017 Hurricane Activity

We will be issuing seasonal updates of our 2017 Atlantic basin hurricane forecasts on **Thursday 1 June**, **Monday 3 July, and Wednesday 2 August**. We will also be issuing two-week forecasts for Atlantic TC activity during the climatological peak of the season from August-October.   A verification and discussion of all 2017 forecasts will be issued in late November 2017. All of these forecasts will be available on our website.

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12 Verification of Previous Forecasts

Table 11: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity from 2012-2016.

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	11.50
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	60
Net Tropical Cyclone Activity	45	45	45	40	81

2016	9 April	Update 1 June	Update 1 July	Update 4 August	Obs.
Hurricanes	6	6	6	6	7
Named Storms	13	14	15	15	15
Hurricane Days	21	21	21	22	26.25
Named Storm Days	52	53	55	55	78.25
Major Hurricanes	2	2	2	2	4
Major Hurricane Days	4	4	4	5	10
Accumulated Cyclone Energy	93	94	95	100	134
Net Tropical Cyclone Activity	101	103	105	110	150