# EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY AND LANDFALL STRIKE PROBABILITY FOR 2019

We anticipate that the 2019 Atlantic basin hurricane season will have slightly below-normal activity.  The current weak El Niño event appears likely to persist and perhaps even strengthen this summer/fall.  Sea surface temperatures averaged across the tropical Atlantic are slightly below normal, and the far North Atlantic is anomalously cool.  Our Atlantic Multi-decadal Oscillation index is below its long-term average. We anticipate a slightly below-average probability for major hurricanes making landfall along the continental United States coastline and in the Caribbean.  As is the case with all hurricane seasons, coastal residents are reminded that it only takes one hurricane making landfall to make it an active season for them.  They should prepare the same for every season, regardless of how much activity is predicted.

(as of 4 April 2019)

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In Memory of William M. Gray[4]

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 2019

| Forecast Parameter and 1981-2010 Average (in parentheses) | Issue Date 4 April 2019 |
|---|---|
| Named Storms (NS) (12.1) | 13 |
| Named Storm Days (NSD) (59.4) | 50 |
| Hurricanes (H) (6.4) | 5 |
| Hurricane Days (HD) (24.2) | 16 |
| Major Hurricanes (MH) (2.7) | 2 |
| Major Hurricane Days (MHD) (6.2) | 4 |
| Accumulated Cyclone Energy (ACE) (106) | 80 |
| Net Tropical Cyclone Activity (NTC) (116%) | 90 |

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

1) Entire continental U.S. coastline - 48% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida - 28% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 28% (average for last century is 30%)

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

1) 39% (average for last century is 42%)

# ABSTRACT

Information obtained through March 2019 indicates that the 2019 Atlantic hurricane season will have activity slightly below the 1981-2010 average. We estimate that 2019 will have about 5 hurricanes (average is 6.4), 13 named storms (average is 12.1), 50 named storm days (average is 59.4), 16 hurricane days (average is 24.2), 2 major (Category 3-4-5) hurricanes (average is 2.7) and 4 major hurricane days (average is 6.2). The probability of U.S. major hurricane landfall is estimated to be about 90 percent of the long-period average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2019 to be approximately 75 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. For the first time, we are also using a statistical/dynamical model based off of data from the ECMWF System 5 as an additional forecast guidance tool.

The current weak El Niño event appears likely to maintain intensity or perhaps even strengthen during the summer/fall. The tropical Atlantic is slightly cooler than normal, while the subtropical Atlantic is quite warm, and the far North Atlantic is anomalously cool. The anomalously cold sea surface temperatures in the far North Atlantic lead us to believe that the Atlantic Multi-decadal Oscillation is in its negative phase. There is considerable uncertainty as to what the configuration of Atlantic sea surface temperatures will look like for the peak of the Atlantic hurricane season.

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.

The early April forecast is the earliest seasonal forecast issued by Colorado State University and has modest long-term skill when evaluated in hindcast mode. The skill of CSU's forecast updates increases as the peak of the Atlantic hurricane season approaches.

# 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 and statistical/dynamical hybrid models show strong evidence on nearly 40 years of data that significant improvement over a climatological forecast can be attained. We would never issue a seasonal hurricane forecast unless we had models developed over a long hindcast period which showed skill.

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 and dynamical models which 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

# 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.

Standard Deviation (SD) – A measure used to quantify the variation in a dataset.

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 36th 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 and a new statistical/dynamical model that both show skill at predicting hurricane activity on nearly 40 years of past data. Qualitative adjustments are added to accommodate additional processes which may not be explicitly represented by either of these 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 are 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 and uses a total of four predictors. The Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) was 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 and correlates with ACE at 0.54 from 1982-2018.

Figure 2 displays the locations of each of our predictors, while Table 1 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. Table 2 displays the 2019 observed values for each of the four predictors in the statistical forecast scheme. Table 3 displays the statistical model output for the 2019 hurricane season. Three of the four predictors are negative for Atlantic hurricane activity, while one predictor (tropical Atlantic SST) is slightly positive.
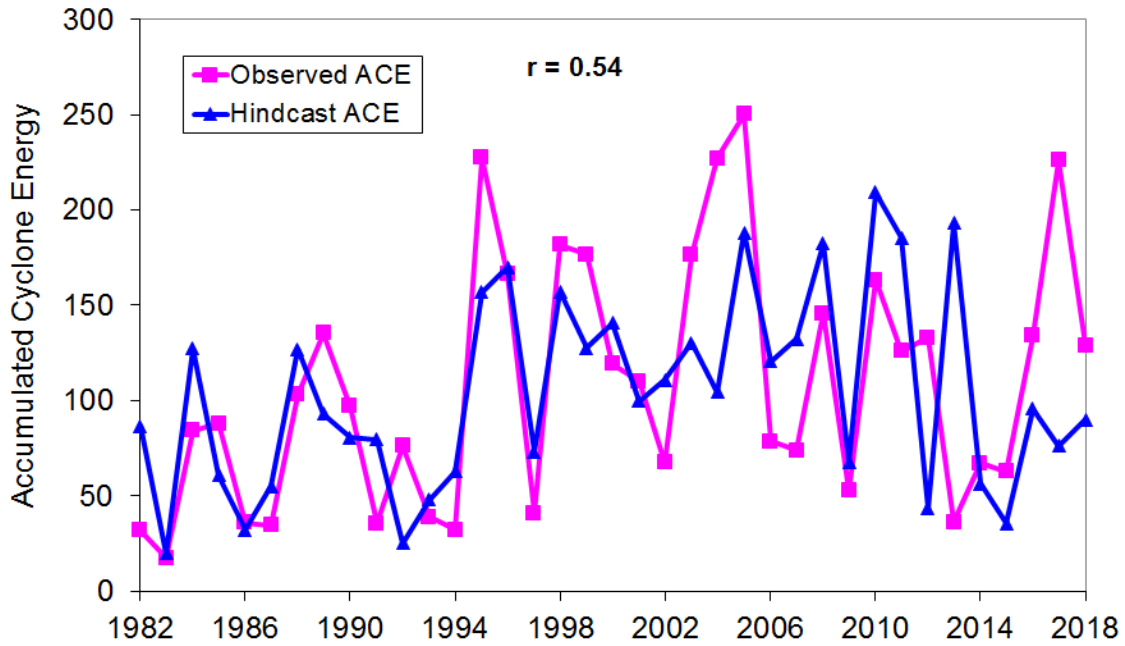


Figure 1: Observed versus early April hindcast values of ACE for 1982-2010 along with real-time forecast values for 2011-2018.

## April Forecast Predictors
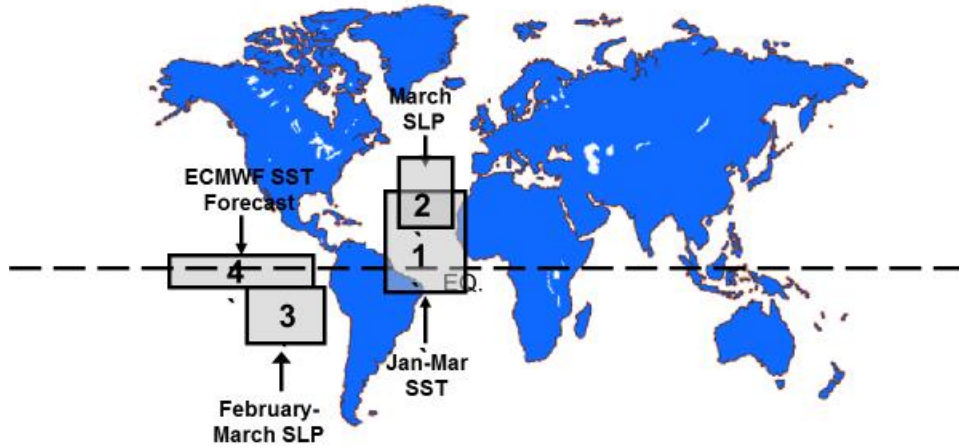


Figure 2: Location of predictors for our early April extended-range statistical prediction for the 2019 hurricane season.

Table 1: 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 2: Listing of 1 April 2019 predictors for the 2019 hurricane season. A plus (+) means that positive deviations of the parameter are associated with increased hurricane activity, while a minus (-) means that negative deviations of the parameter are associated with increased hurricane activity. SD stands for standard deviation.

| Predictor | 2019 Forecast Value | Impact on 2019 TC Activity |
|---|---|---|
| 1) Jan-Mar Atlantic SST (5°S-35°N, 10-40°W) (+) | +0.3 SD | Slightly Increase |
| 2) Mar SLP (20-40°N, 20-35°W) (-) | +0.8 SD | Decrease |
| 3) Feb-Mar SLP (5-20°S, 85-120°W) (+) | -0.7 SD | Decrease |
| 4) ECMWF 1 Mar SST Forecast for Sep Nino 3 (5°S-5°N, 90-150°W) (-) | +0.8 SD | Decrease |

Table 3: Statistical model output for the 2019 Atlantic hurricane season and the final adjusted forecast.

| Forecast Parameter and 1981-2010 Average (in parentheses) | Statistical Forecast | Final Forecast |
|---|---|---|
| Named Storms (NS) (12.1) | 9.0 | 13 |
| Named Storm Days (NSD) (59.4) | 40.1 | 50 |
| Hurricanes (H) (6.4) | 4.8 | 5 |
| Hurricane Days (HD) (24.2) | 16.2 | 16 |
| Major Hurricanes (MH) (2.7) | 1.6 | 2 |
| Major Hurricane Days (MHD) (6.2) | 3.1 | 4 |
| Accumulated Cyclone Energy (ACE) (106) | 67 | 80 |
| Net Tropical Cyclone Activity (NTC) (116%) | 75 | 90 |

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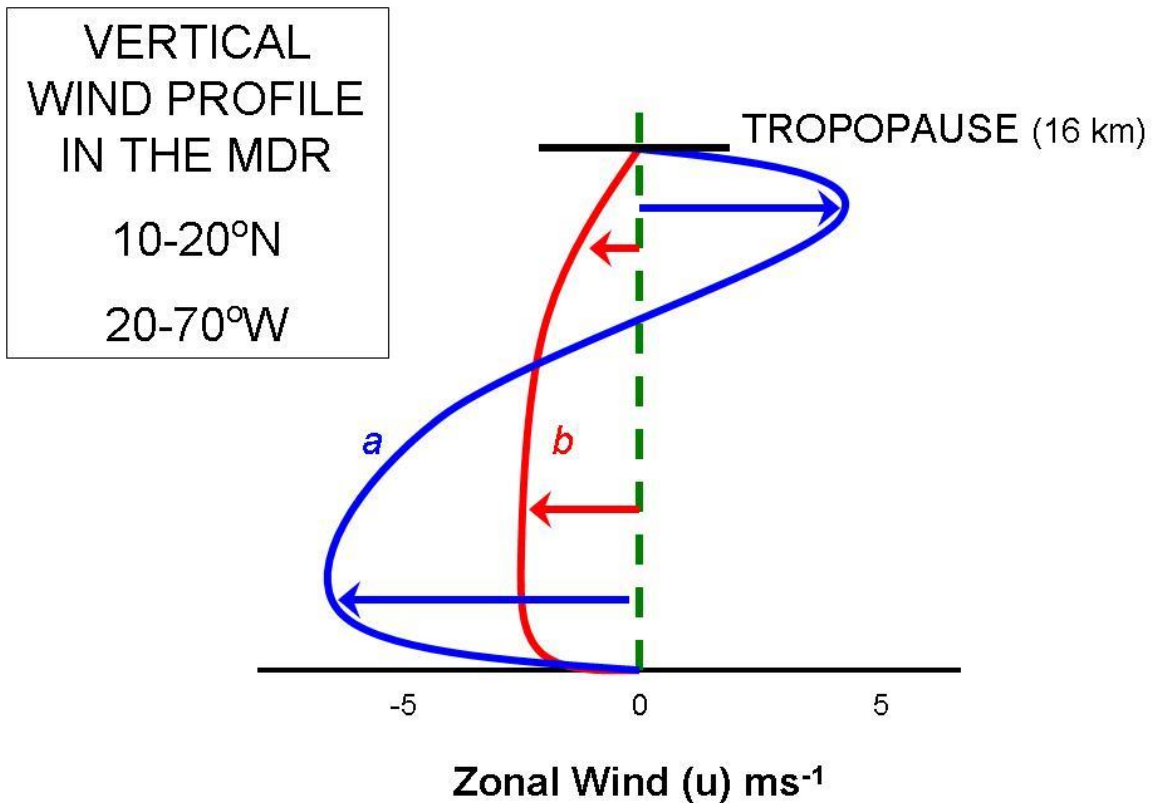
Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of vertical wind shear.

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.

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

(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 ACE. 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. March SLP in the Subtropical Atlantic (-)

(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.

### Predictor 3. February-March SLP in the southeastern tropical Pacific (+)

(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.

### Predictor 4. ECMWF 1 March SST Forecast for September Nino 3 (-)

(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 for system 4 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).  System 5, the latest ensemble prediction system recently released by ECMWF, has slightly improved ENSO prediction skill from system 4.

**August-October Correlations w/ Predictor 1 (1982-2010) (+)**

(a)   SST

(b)   SLP
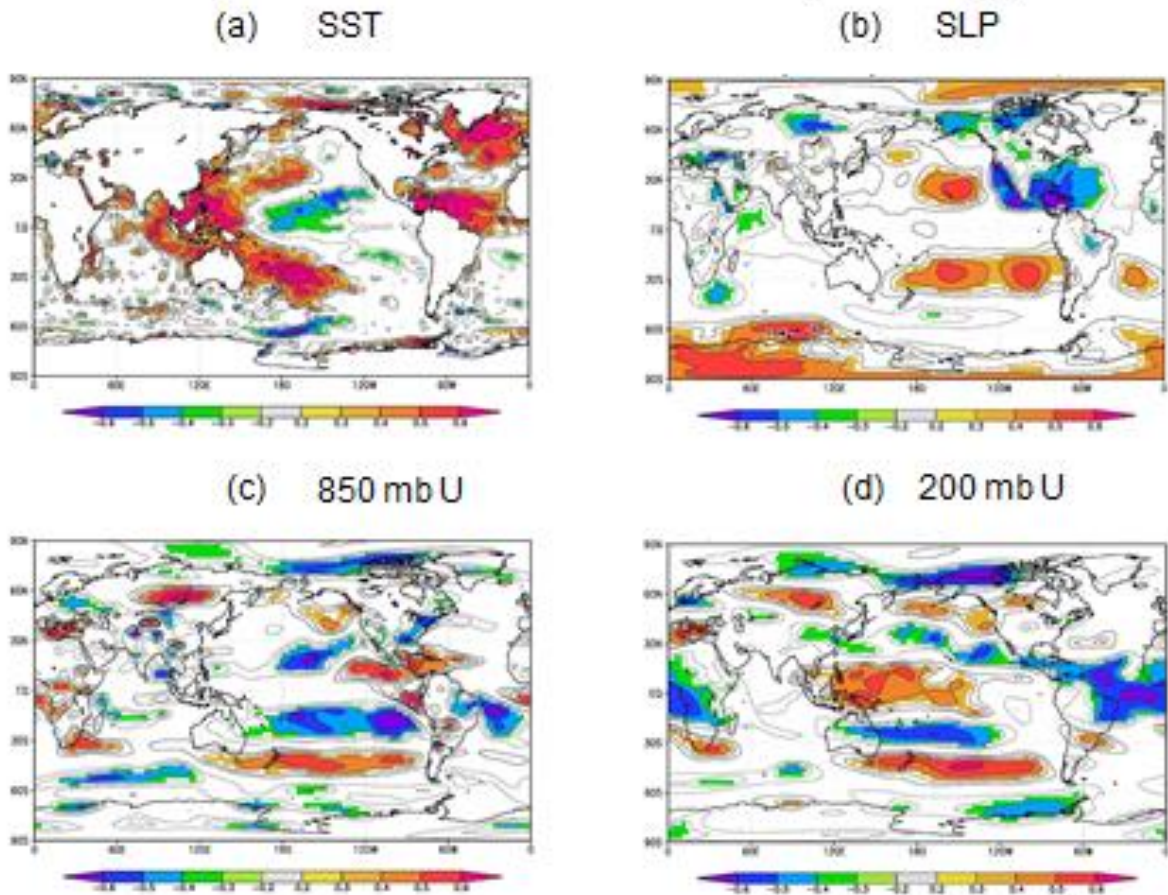
(c)   850 mb U

(d)   200 mb U

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.
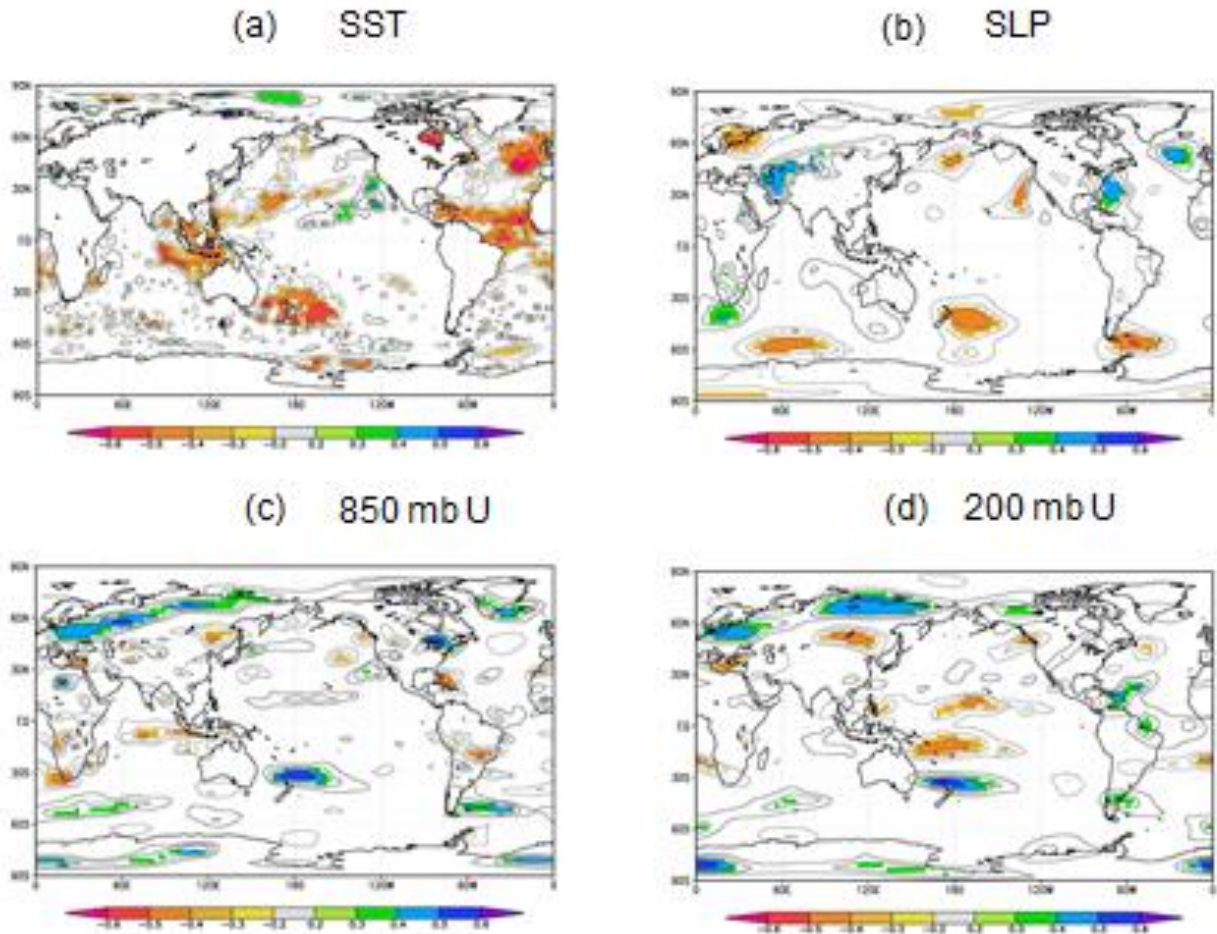
Figure 5:  Linear correlations between March SLP in the subtropical Atlantic (Predictor 2) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).  The predictor's primary 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.**

## August-October Correlations w/ Predictor 3 (1982-2010) (+)

### (a)   SST

### (b)   SLP

### (c)   850 mb U

### (d)   200 mb U



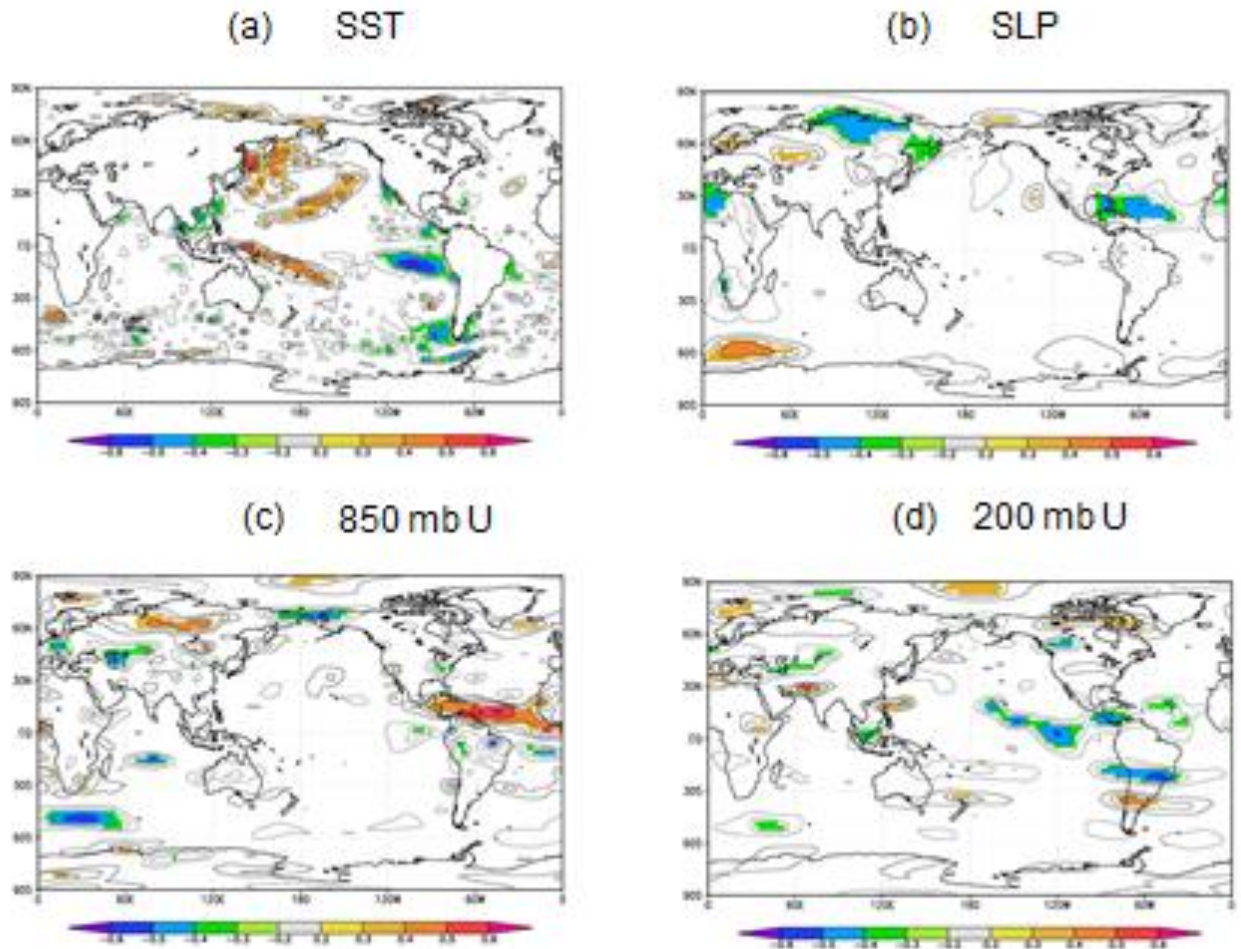Figure 6:  Linear correlations between February-March SLP in the southern tropical Pacific (Predictor 3) and August-October sea surface temperature (panel a), August-October sea level pressure (panel b), August-October 850 mb zonal wind (panel c) and August-October 200 mb zonal wind (panel d).  The predictor's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

## August-October Correlations w/ Predictor 4 (1982-2010) (-)

(a)  SST

(b)  SLP
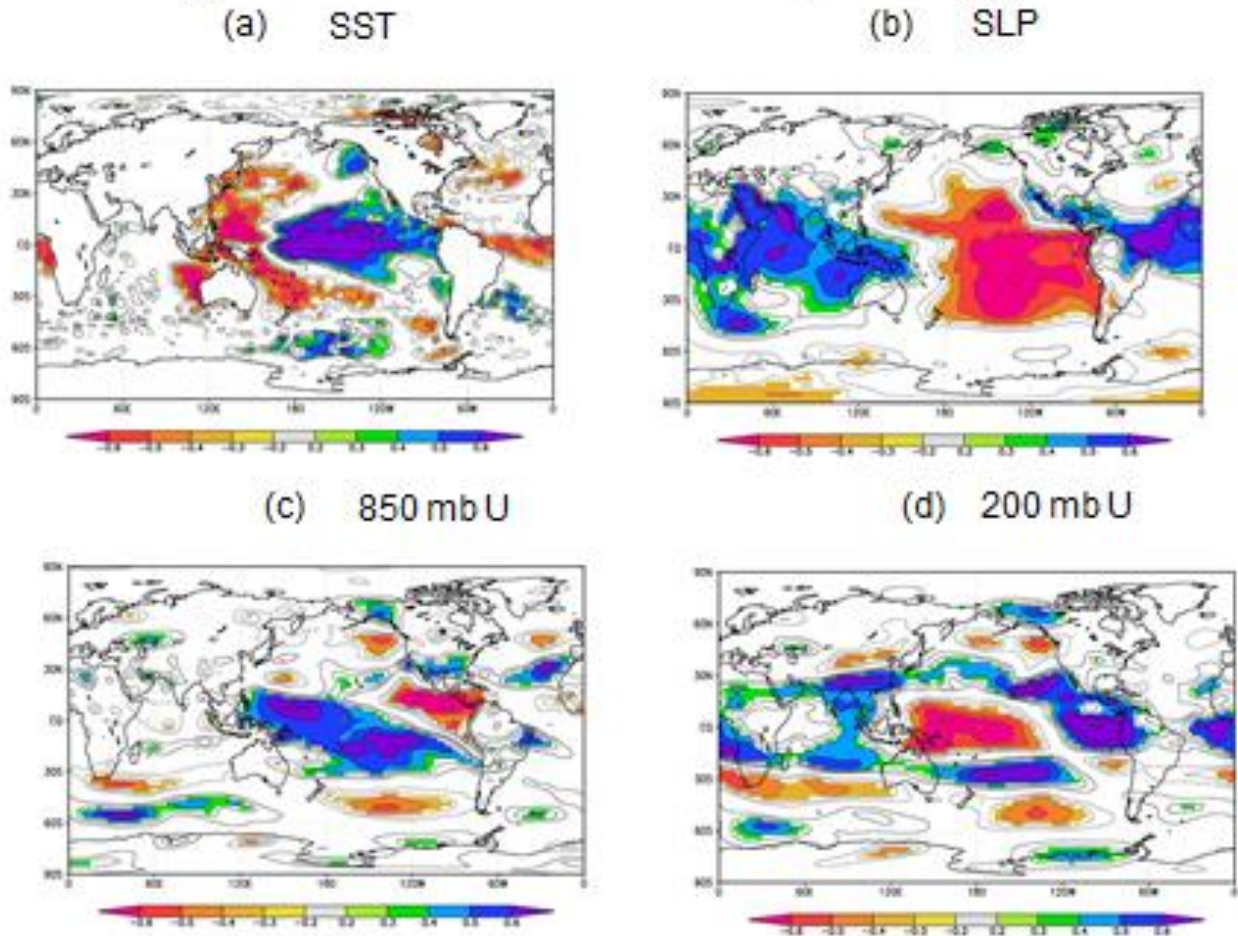
(c)  850 mb U

(d)  200 mb U

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.**

## 2.2     April Statistical/Dynamical Forecast Scheme

We have developed a new statistical/dynamical hybrid forecast model scheme this year.  This model, developed in partnership with Louis-Philippe Caron and the data team at the Barcelona Supercomputing Centre, uses output from the ECMWF System 5 model to forecast the input to our early August statistical forecast model.  The early August statistical forecast model shows the highest level of skill of any of our statistical models, since it is the model released just before the peak of the Atlantic hurricane season in September.  ECMWF System 5 is able to forecast the large-scale fields that go into the

early August statistical forecast model with considerable skill by March. We then use the forecasts of the individual parameters to forecast ACE for the 2019 season. It typically takes about ten days after the initialization date to obtain System 5 output, so the results displayed below are from the model output from the 1 March forecast.

Figure 8 displays the parameters used in our early April statistical model, while Table 4 displays System 5's forecasts of these parameters for 2019. Two of the three parameters call for below-normal activity, while the temperatures in the subtropical eastern Atlantic strongly favor above-normal activity. However, the ECMWF System 5 is calling for extremely warm surface temperatures throughout most of the global oceans in July, and it is the gradient in temperatures between the Atlantic and the rest of the tropics that is important (e.g., relative SST). Figure 9 displays hindcast data of the System 5 forecast of ACE from 1981-2018. Table 5 presents the forecast from System 5, which calls for a slightly above-average season given its forecast of warm temperatures in the eastern subtropical Atlantic.

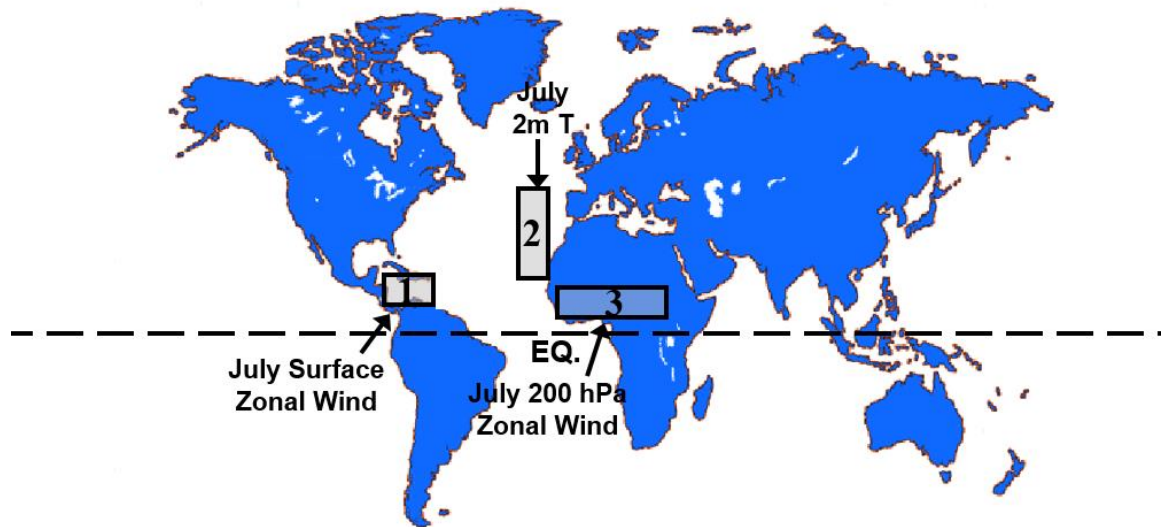## Post-31 July Seasonal Forecast Predictors



Figure 8: Location of predictors for our April statistical/dynamical extended-range statistical prediction for the 2019 hurricane season. This forecast uses ECMWF System 5 to predict July conditions in the three boxes displayed and uses those predictors to forecast ACE.

Table 4: Listing of predictions of July large-scale conditions from ECMWF System 5 output, initialized on 1 March. A plus (+) means that positive deviations of the parameter are associated with increased hurricane activity, while a minus (-) means that negative deviations of the parameter are associated with increased hurricane activity.

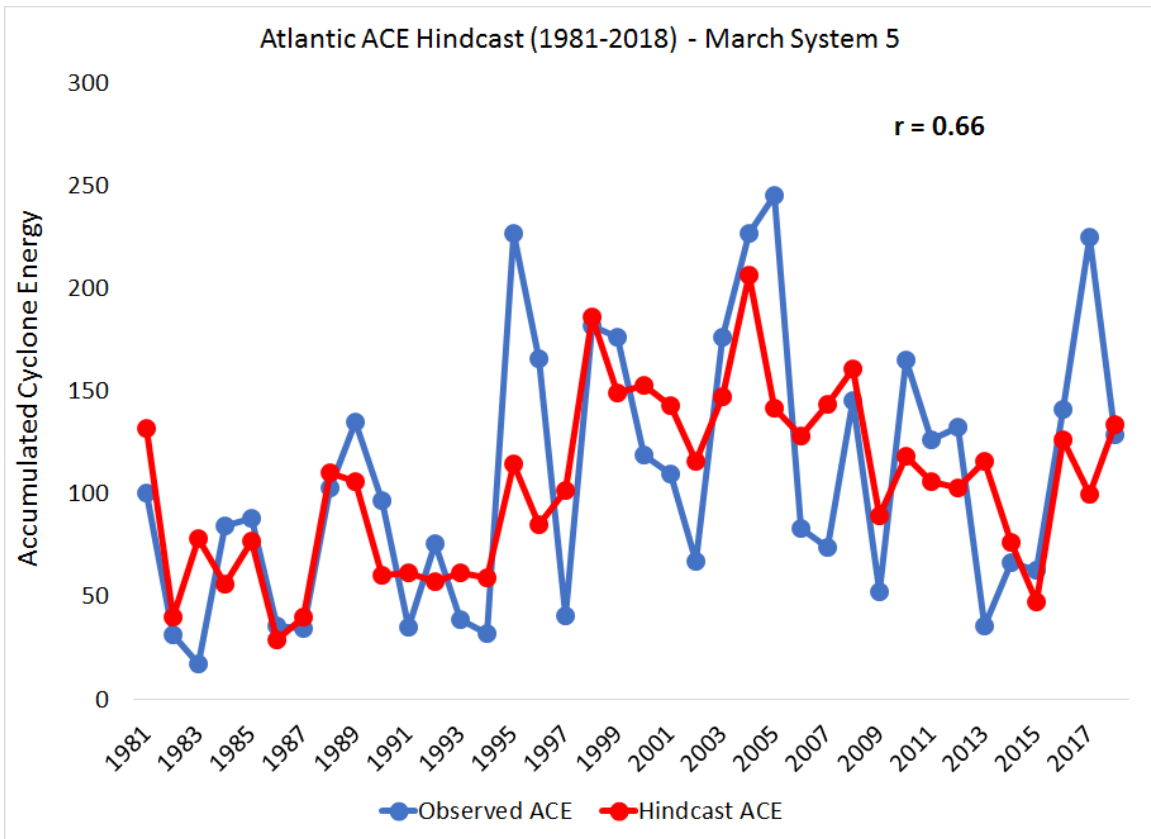| Predictor | Values for 2019 Forecast | Effect on 2019 Hurricane Season |
|---|---|---|
| 1) ECMWF Prediction of July Surface U (10-17.5°N, 60-85°W) (+) | -1.1 SD | Suppress |
| 2) ECMWF Prediction of July 2-Meter Temperature (20-40°N, 15-35°W) (+) | +1.6 SD | Enhance |
| 3) ECMWF Prediction of July 200 mb U (5-15°N, 0-40°E) (-) | +1.0 SD | Suppress |



Figure 9: Observed versus hindcast ACE values using the statistical/dynamical hybrid model, initialized on 1 March.

Table 5: Statistical/dynamical model output for the 2019 Atlantic hurricane season and the final adjusted forecast.

| Forecast Parameter and 1981-2010 Average (in parentheses) | Statistical/Dynamical Hybrid Forecast | Final Forecast |
|---|---|---|
| Named Storms (12.1) | 12.3 | 13 |
| Named Storm Days (59.4) | 64.3 | 50 |
| Hurricanes (6.4) | 7.3 | 5 |
| Hurricane Days (24.2) | 30.5 | 16 |
| Major Hurricanes (2.7) | 3.4 | 2 |
| Major Hurricane Days (6.2) | 8.5 | 4 |
| Accumulated Cyclone Energy Index (106) | 127 | 80 |
| Net Tropical Cyclone Activity (116%) | 135 | 90 |

## 2.3    April Analog Forecast Scheme

Certain years in the historical record have global oceanic and atmospheric trends which are similar to 2019. These years also provide useful clues as to likely levels of activity that the forthcoming 2019 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 2019 conditions as well as projected August-October 2019 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 weak to moderate El Niño conditions during August-October. We selected years that tended to have near-average SSTs in the tropical Atlantic. We anticipate that the 2019 hurricane season will have activity near the average of our five analog years.

Table 6: Best analog years for 2019 with the associated hurricane activity listed for each year.

| Year | NS | NSD | H | HD | MH | MHD | ACE | NTC |
|---|---|---|---|---|---|---|---|---|
| 1969 | 18 | 92.25 | 12 | 40.25 | 5 | 6.50 | 166 | 182 |
| 1987 | 7 | 37.25 | 3 | 5.00 | 1 | 0.50 | 34 | 46 |
| 1991 | 8 | 24.25 | 4 | 8.25 | 2 | 1.25 | 36 | 58 |
| 2002 | 12 | 57.00 | 4 | 10.75 | 2 | 3.00 | 67 | 83 |
| 2009 | 9 | 30.00 | 3 | 12.00 | 2 | 3.50 | 53 | 69 |
| Average | 10.8 | 48.2 | 5.2 | 15.3 | 2.4 | 3.0 | 71 | 87 |
| **2019 Forecast** | **13** | **50** | **5** | **16** | **2** | **4** | **80** | **90** |

## 2.4    April Forecast Summary and Final Adjusted Forecast

Table 7 shows our final adjusted early April forecast for the 2019 season which is a combination of our statistical scheme, our statistical/dynamical scheme, our analog scheme and qualitative adjustments for other factors not explicitly contained in any of these schemes. Our analog and statistical schemes call for below-average TC activity, while the statistical/dynamical scheme calls for slightly above-average TC activity. Our forecast is close to the average of the three schemes and calls for a slightly below-normal season, due to what we anticipate will be weak to moderate El Niño conditions for the peak of the Atlantic hurricane season (August-October).

Table 7: Summary of our early April statistical forecast, our statistical/dynamical forecast, our analog forecast, the average of those three schemes and our adjusted final forecast for the 2019 hurricane season.

| Forecast Parameter and 1981-2010 Average (in parentheses) | Statistical Scheme | Statistical/ Dynamical Scheme | Analog Scheme | Average of Three Schemes | Adjusted Final Forecast |
|---|---|---|---|---|---|
| Named Storms (12.1) | 9.0 | 12.3 | 10.8 | 10.7 | 13 |
| Named Storm Days (59.4) | 40.1 | 64.3 | 48.2 | 50.9 | 50 |
| Hurricanes (6.4) | 4.8 | 7.3 | 5.2 | 5.8 | 5 |
| Hurricane Days (24.2) | 16.2 | 30.5 | 15.3 | 20.7 | 16 |
| Major Hurricanes (2.7) | 1.6 | 3.4 | 2.4 | 2.5 | 2 |
| Major Hurricane Days (6.2) | 3.1 | 8.5 | 3.0 | 4.9 | 4 |
| Accumulated Cyclone Energy Index (106) | 67 | 127 | 71 | 88 | 80 |
| Net Tropical Cyclone Activity (116%) | 75 | 135 | 87 | 99 | 90 |

# 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 8 provides our early April final 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 8:  Model hindcast error and our 2019 hurricane forecast.  Uncertainty ranges are given in one standard deviation (SD) increments.

| Parameter | Hindcast Error (SD) | 2019 Forecast | Uncertainty Range – 1 SD (67% of Forecasts Likely in this Range) |
|---|---|---|---|
| Named Storms (NS) | 3 | 13 | 10 – 16 |
| Named Storm Days (NSD) | 21 | 50 | 29 – 71 |
| Hurricanes (H) | 2 | 5 | 3 – 7 |
| Hurricane Days (HD) | 13 | 16 | 3 – 29 |
| Major Hurricanes (MH) | 1 | 2 | 1 – 3 |
| Major Hurricane Days (MHD) | 5 | 4 | 0 – 9 |
| Accumulated Cyclone Energy (ACE) | 53 | 80 | 27 – 133 |
| Net Tropical Cyclone (NTC) Activity | 50 | 90 | 40 – 140 |

## 4    ENSO

The tropical Pacific was characterized by warm neutral ENSO conditions last summer and fall (Figure 10).  ENSO events are partially defined by NOAA based on SST anomalies in the Nino 3.4 region, which is defined as 5°S-5°N, 170-120°W.  Warm neutral ENSO conditions are defined by anomalies between 0°C – 0.5°C. Over the past several months, SST anomalies have increased, and the tropical Pacific is now characterized by weak El Niño conditions (Nino 3.4 between 0.5°C – 1.0°C).  While there was some anomalous cooling during January and February, that process has since reversed, and Nino 3.4 anomalies are now nearly as high as they were during late November.
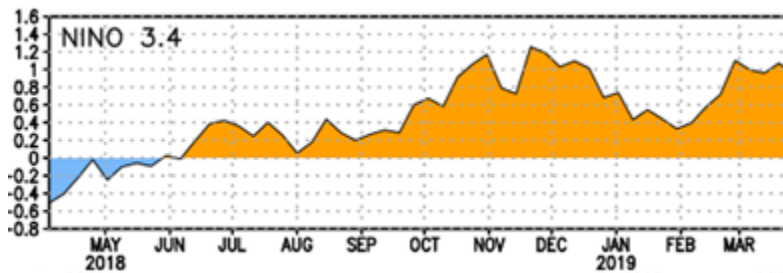


Figure 10:  Nino 3.4 SST anomalies from April 2018 through March 2019.   Figure courtesy of Climate Prediction Center.

Upper-ocean heat content anomalies in the eastern and central tropical Pacific have been at above-normal levels since last spring (Figure 11).  These anomalies had an initial peak during mid-October.  After anomalous cooling during the late fall and early winter, upper ocean heat content anomalies have again increased and are currently near 1.4°C.  Only two Marches on record (since 1979) have had upper-ocean heat content anomalies greater than 1.4°C.  Those two seasons were 2014 and 2015.  The summer/fall of 2014 ended up with warm neutral ENSO conditions, while the summer/fall of 2015 was characterized by a strong El Niño event.
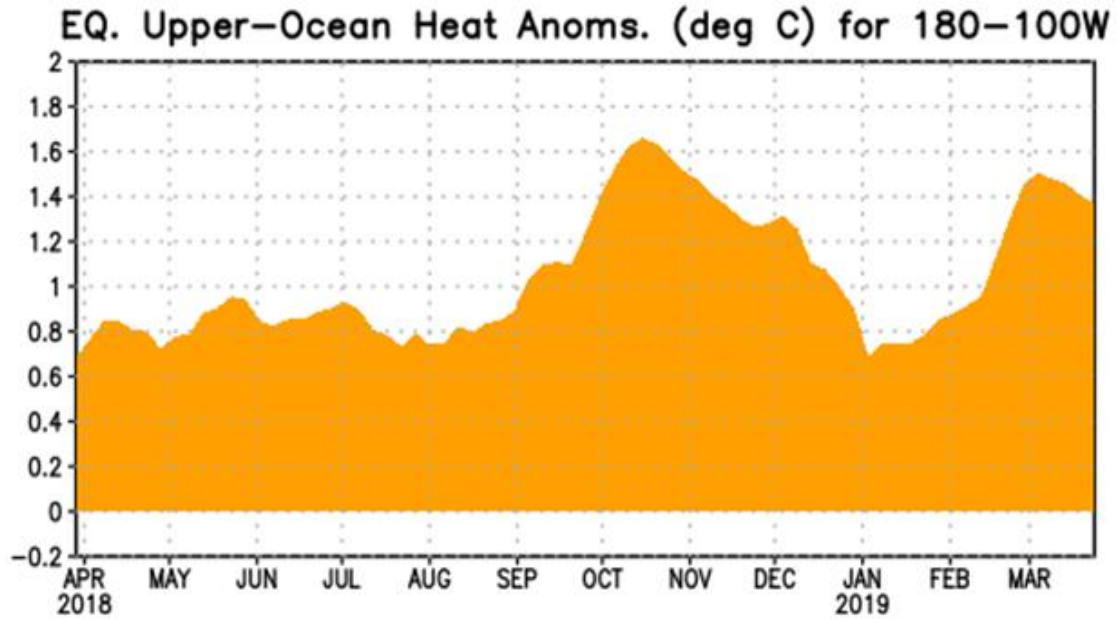
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Figure 11: Central and eastern equatorial Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Upper ocean heat content anomalies have generally been increasing since January 2019.

SSTs are above normal across the eastern and central tropical Pacific and slightly below normal in portions of the western tropical Pacific (Figure 12). This is to be expected given the weak El Niño conditions that are present across the basin.
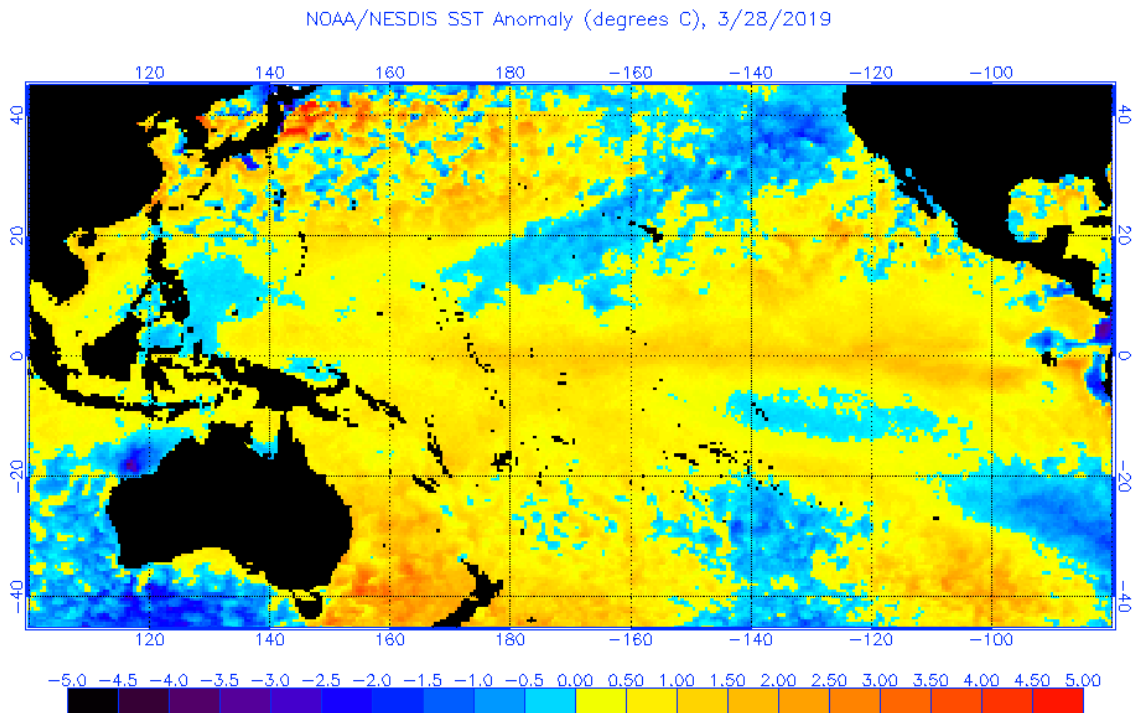


Figure 12: Current SST anomalies across the tropical and subtropical Pacific.

Table 9 displays January and March SST anomalies for several Nino regions. Anomalies have trended slightly upward over the past couple of months across the central tropical Pacific, with slight anomalous cooling in the eastern tropical Pacific. These SST trends are in keeping with most of the forecast model guidance (as shown in the next few pages), as well as the official forecast from NOAA that indicates a likely persistence of El Niño conditions for the next several months.

Table 9: 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 | +0.9 | +0.4 | -0.5 |
| Nino 3 | +0.6 | +0.8 | +0.2 |
| Nino 3.4 | +0.7 | +1.0 | +0.3 |
| Nino 4 | +0.8 | +0.9 | +0.1 |

The tropical Pacific experienced a downwelling (warming) Kelvin wave (denoted by the long dashed line) that temporarily pushed the basin to borderline weak El Niño conditions early last summer (Figure 13). Following an upwelling (cooling) Kelvin wave (denoted by the short dashed line) in December, an additional downwelling Kelvin wave propagated across the tropical Pacific, driving the formation of weak El Niño conditions. While upwelling Kelvin waves sometimes follow downwelling Kelvin waves, there appears to be little sign of a cooling wave across the tropical Pacific at this time, likely due to the lack of strong trade winds (to be discussed in the following paragraphs).
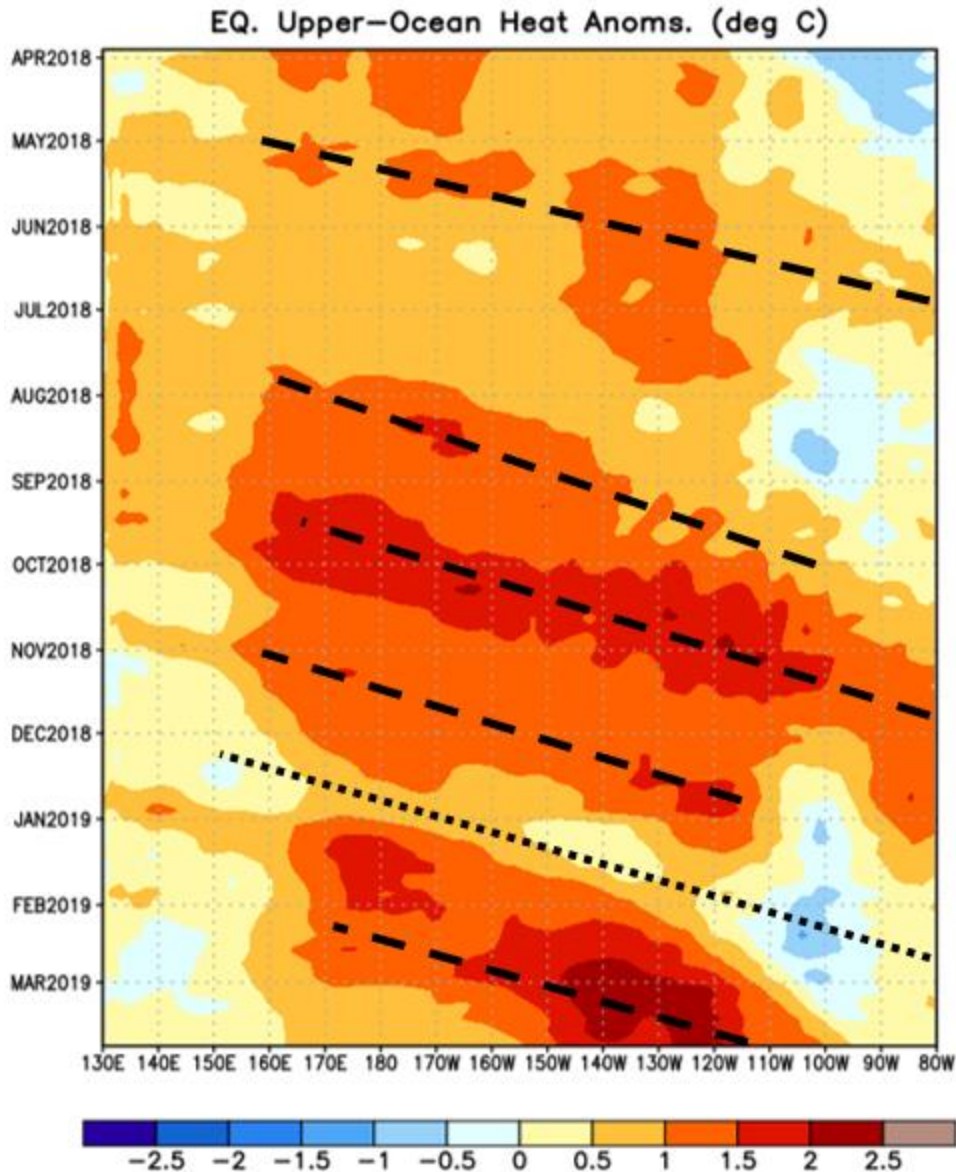
**EQ. Upper-Ocean Heat Anoms. (deg C)**

Figure 13: Upper-ocean heat content anomalies in the tropical Pacific since April 2018. 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.

Over the next several months, we will be closely monitoring low-level winds over the tropical Pacific. Typically, when strong low-level westerly anomalies are observed across portions of the western and central tropical Pacific (a phenomenon known as a westerly wind burst), downwelling Kelvin waves are triggered that can cause a transition to or can reinforce existing El Niño conditions. Anomalous westerlies are currently observed across the central tropical Pacific and are forecast to persist for the next several weeks (Figure 14). Consequently, we do not see anything in the short-term that would lead to a rapid weakening of El Niño conditions. The Madden-Julian Oscillation (MJO),

which is an important driver of sub-seasonal variability of lower- and upper-level winds, is predicted to be fairly weak for the next several weeks (Figure 15). Consequently, we believe that the current low-frequency variability which favors anomalous westerly winds across the tropical Pacific is likely to persist for the next few weeks.
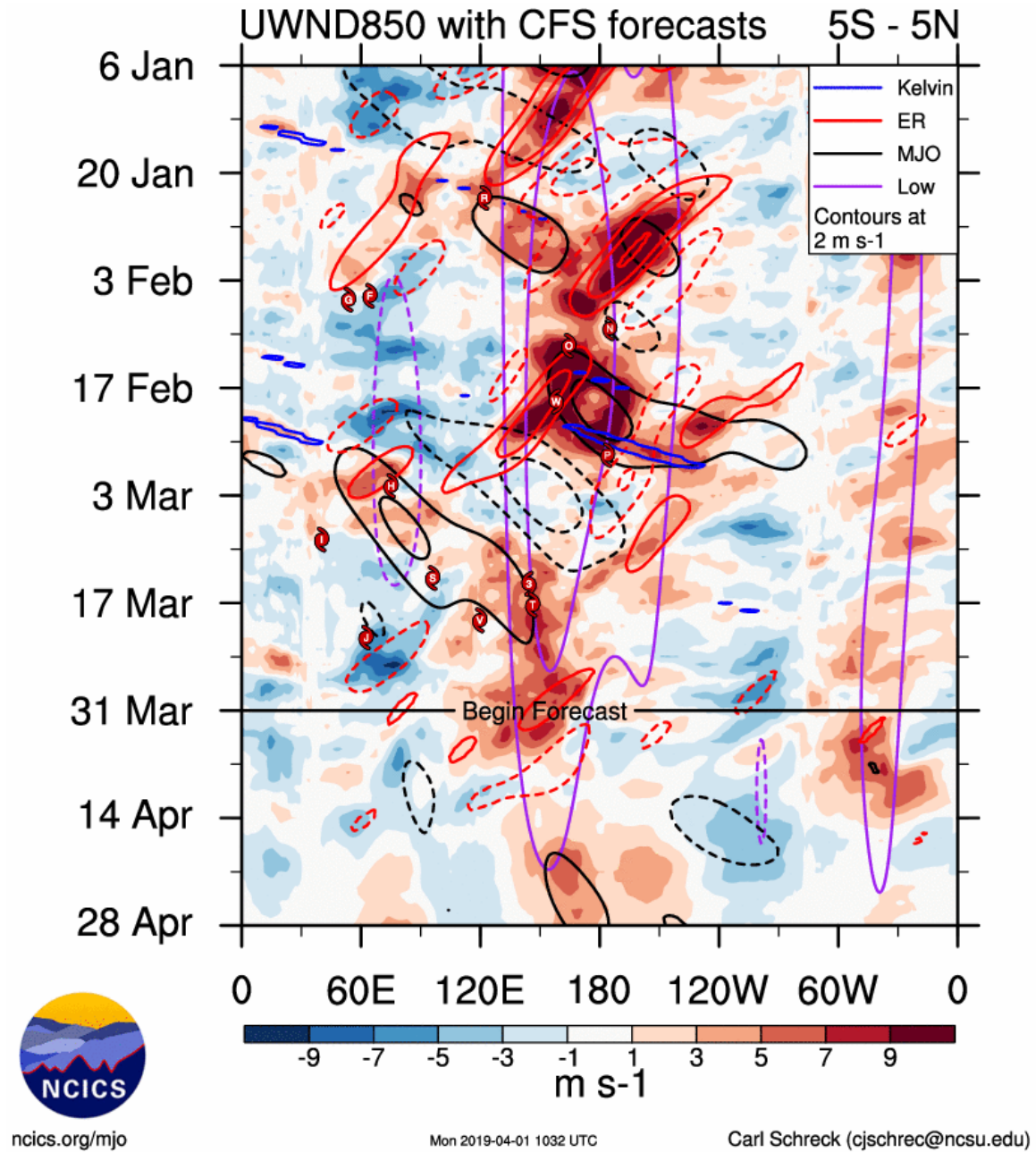


Figure 14: Observed low-level winds across the equatorial region as well as predictions for the next four weeks by the Climate Forecast System. Figure courtesy of Carl Schreck.
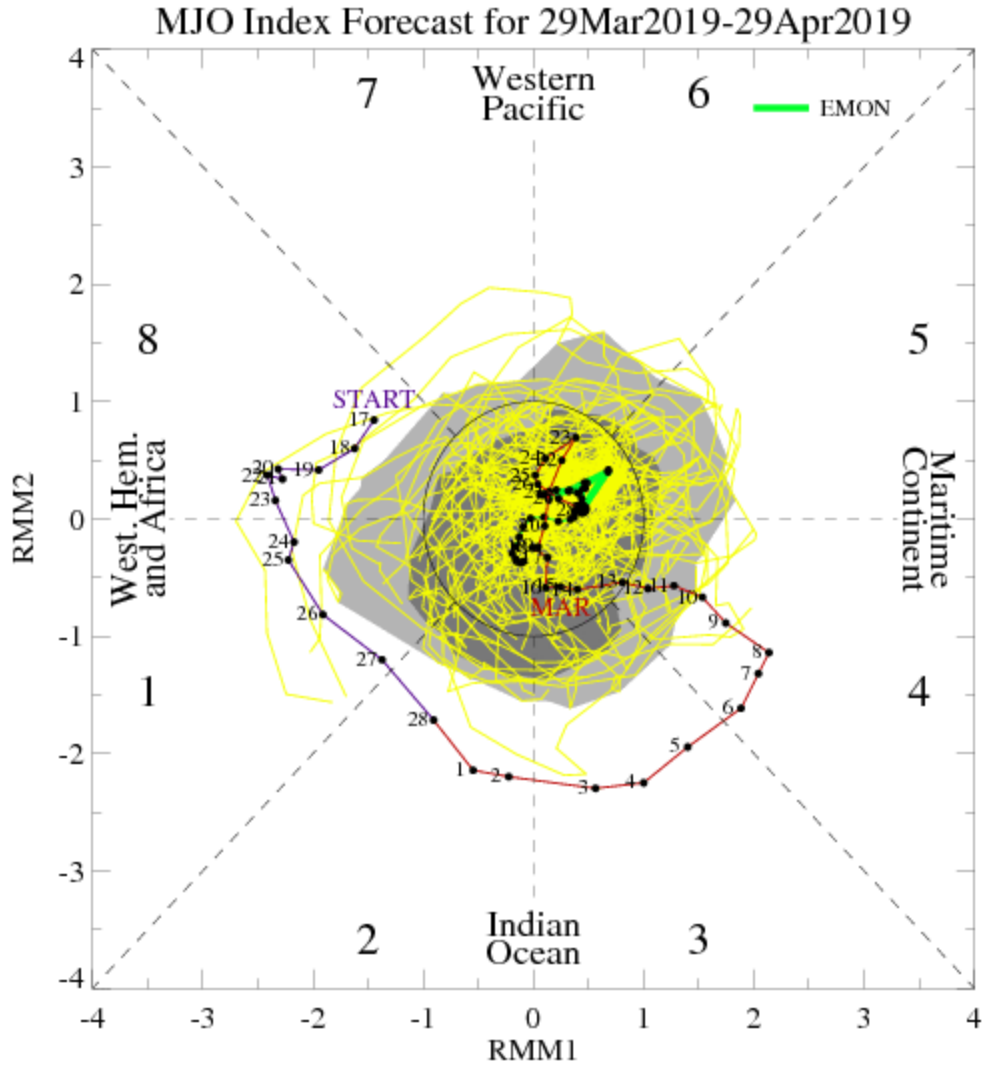
Figure 15: Monthly forecast of the MJO from the ECMWF model. The ECMWF model generally calls for weak MJO conditions for the next several weeks.

There is always considerable uncertainty with the future state of El Niño during the spring. The latest plume of ENSO predictions from several statistical and dynamical models shows a large spread by the peak of the Atlantic hurricane season in August-October (Figure 16). About 2/3 of all forecast models are calling for El Niño conditions to persist through August-October, with the remaining models calling for warm neutral ENSO conditions.
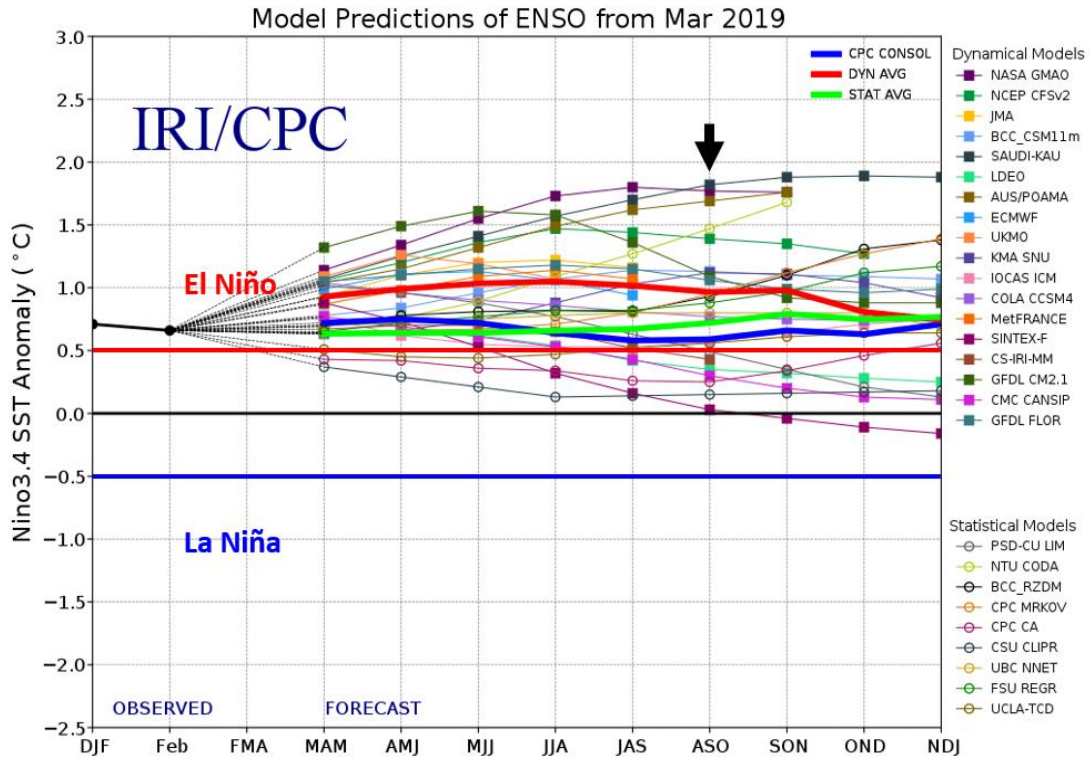
Figure 16: ENSO forecasts from various statistical and dynamical models for the Nino 3.4 SST anomaly based on late February to early March initial conditions. About 2/3 of all forecast models are calling for El Niño conditions to persist through August-October (black arrow), which is the climatological peak of the Atlantic hurricane season. Figure courtesy of the International Research Institute (IRI).

The European Centre for Medium-Range Weather Forecasts (ECMWF) is generally considered to be one of the most skillful models at predicting ENSO. However, the ECMWF model, like all ENSO forecast models, has significant challenges forecasting through the Northern Hemisphere springtime predictability barrier. A good discussion of the ENSO springtime predictability barrier was published by NOAA a few years ago.

The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately +0.8°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.
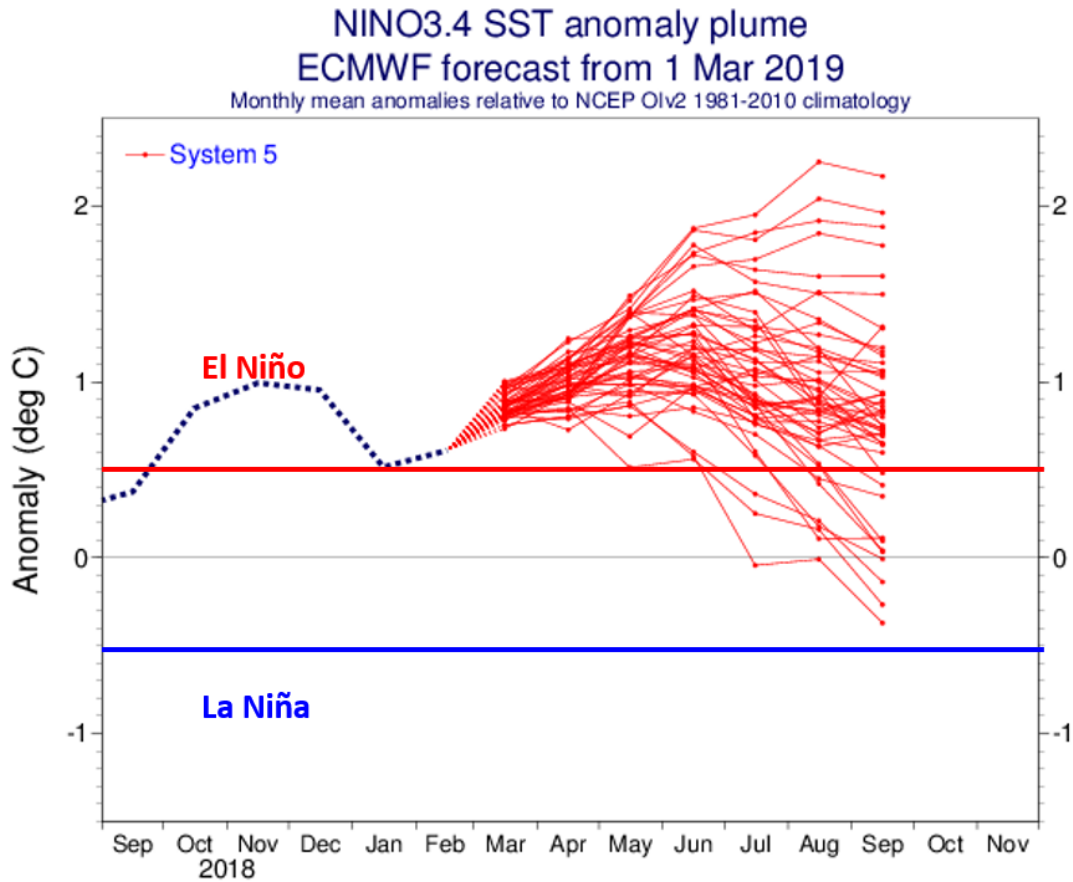
28

Figure 17: ECMWF ensemble model forecast for the Nino 3.4 region. About 80% of ensemble members are calling for continued El Niño conditions through September.

Based on the above information, our best estimate is that we will likely have weak El Niño conditions for 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 slightly more confident about ENSO conditions for the peak of the upcoming hurricane season by the time of our next forecast on 4 June.

## 5 Current Atlantic Basin Conditions

The current SST pattern across the North Atlantic basin is characterized by relatively cold SSTs in the far North Atlantic, warm SST anomalies off of the East Coast of the United States and slightly colder than normal anomalies in the tropical Atlantic. This type of SST pattern is typically what would be expected with a negative phase of the Atlantic Multi-decadal Oscillation (AMO), although the warm anomalies off of the US East Coast are somewhat stronger than has been observed with previous negative AMO phases (Figure 18).
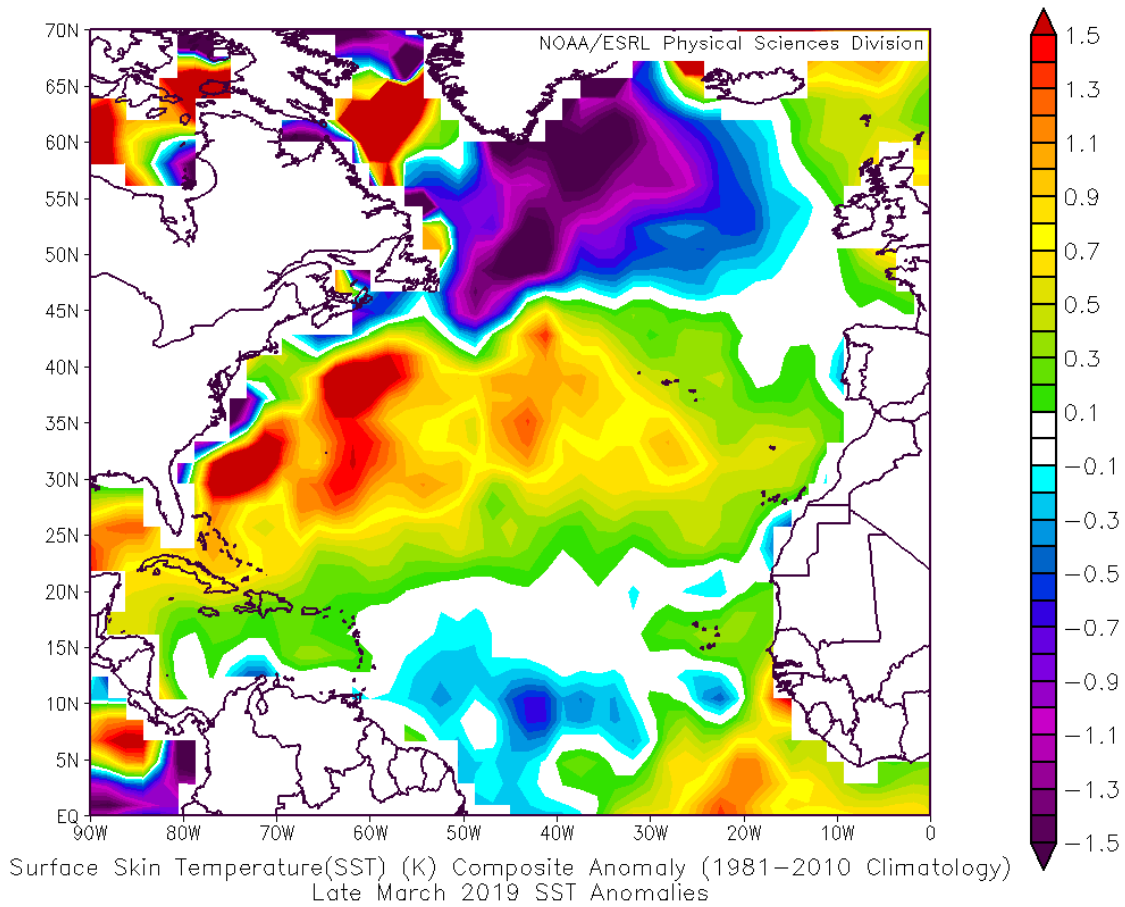
Figure 18: Late March 2019 SST anomaly pattern across the Atlantic Ocean.

The Atlantic generally had a similar anomalous SST pattern at the end of last year's hurricane season (late November 2018) (Figure 19). We tended to have a positive phase of the North Atlantic Oscillation (NAO) through the winter of 2018/19 (Figure 20), which forces a tripole pattern of SSTs characterized by anomalous warmth off of the US East Coast and anomalous cold in the far North Atlantic and in the tropical Atlantic.

Figure 19: Late November 2018 North Atlantic SST anomalies.



Figure 20: Observed standardized values of the daily NAO since December 2018. The NAO has generally been positive throughout the winter of 2018/19.

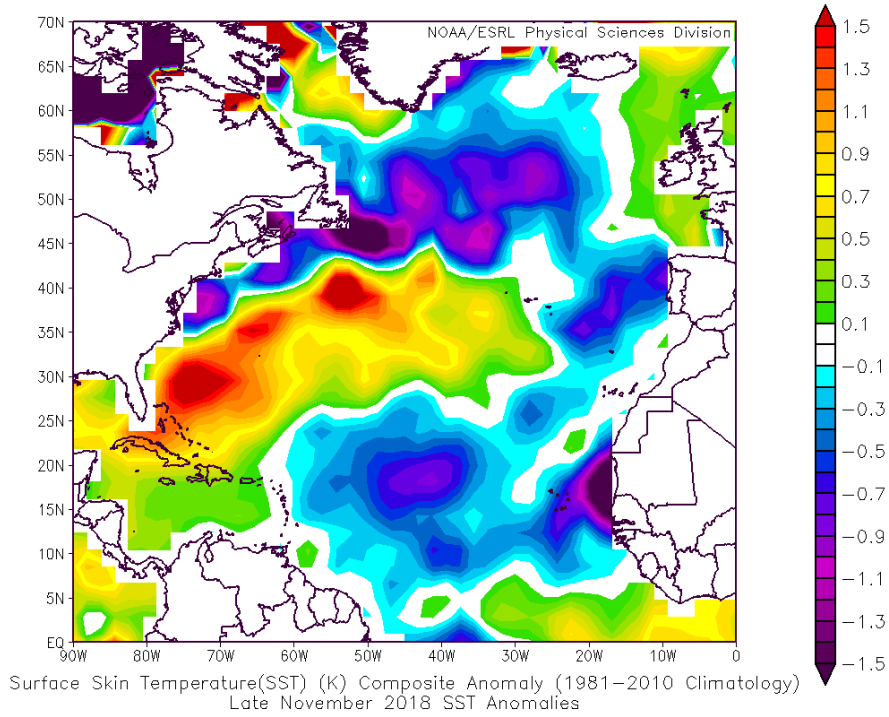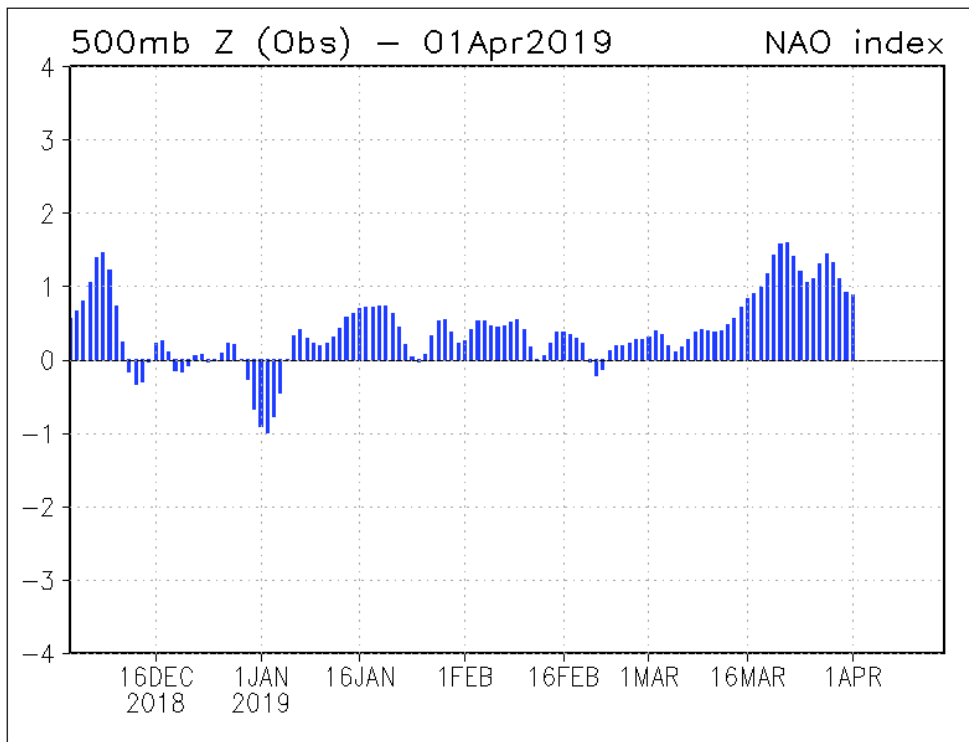While there is considerable uncertainty as to what the tropical Atlantic SSTs will look like during August-October of 2019, the current SST anomalies are tracking in line with below-average Atlantic hurricane seasons in previous years (Figure 21). As can be seen in the figure below, however, there is little spread between below-average, average and above-average hurricane seasons in late March. This indicates that there is still a considerable amount of uncertainty as to how active the 2019 hurricane season is likely to be given current SSTs in the tropical Atlantic.
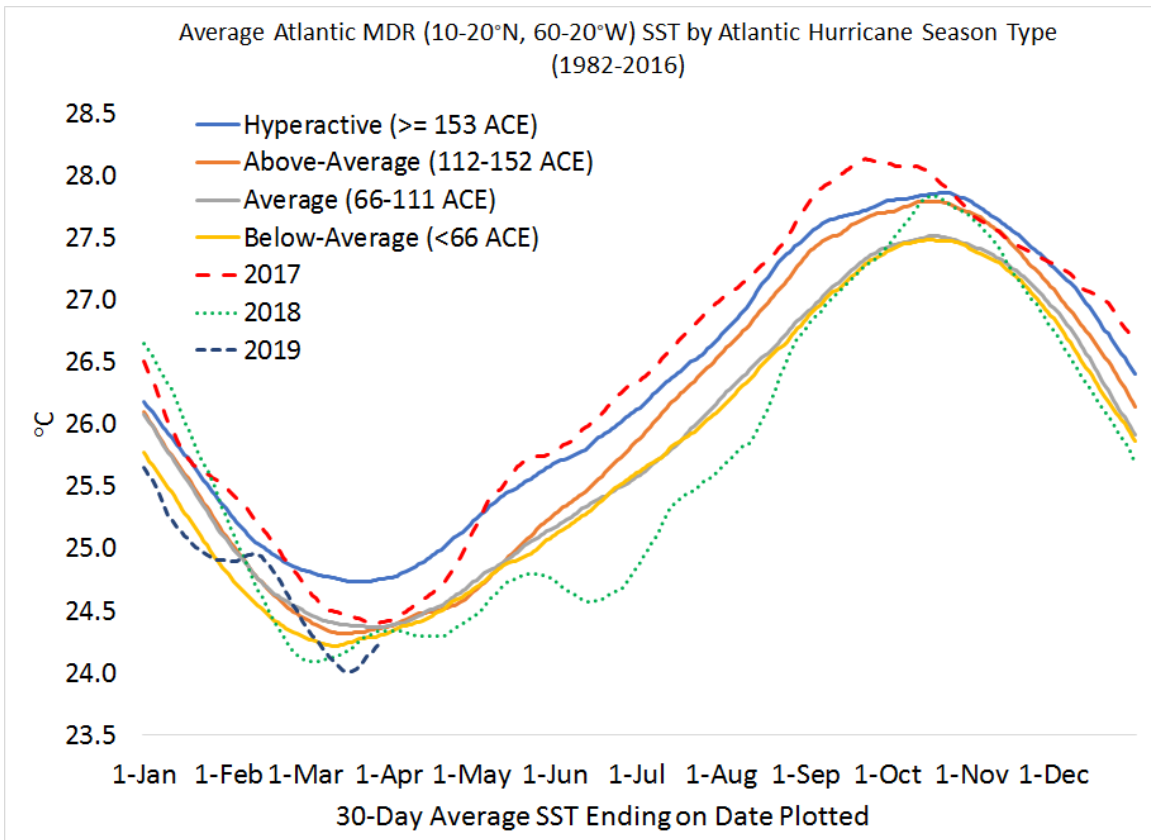


Figure 21: Tropical Atlantic SST anomalies plotted for the average of various Atlantic hurricane season types from 1982-2016. Also plotted are 30-day running averages of SSTs for 2017, 2018 and 2019. Note, however, that there is very little spread between below-average, average and above-average hurricane seasons in late March.

# 6      Landfall Probabilities for 2019

A significant focus of our recent research involves efforts to develop forecasts of the probability of hurricane landfall along the continental 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 to be 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 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 10: 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 11 lists landfall probabilities for the 2019 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 2019 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 11: 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 2019. 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) | 76% (79%) | 64% (68%) | 48% (52%) | 81% (84%) | 95% (97%) |
| Gulf Coast (Regions 1-4) | 55% (59%) | 39% (42%) | 28% (30%) | 56% (60%) | 80% (83%) |
| Florida plus East Coast (Regions 5-11) | 47% (50%) | 41% (44%) | 28% (31%) | 57% (61%) | 77% (81%) |
| Caribbean (10-20°N, 60-88°W) | 79% (82%) | 53% (57%) | 39% (42%) | 71% (75%) | 94% (96%) |

# 7      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, as well as output from dynamical models, indicate that 2019 should have slightly below-average activity.  The big question marks with this season's predictions are whether El Niño persists, as well as what the configuration of SSTs will look like in Atlantic Ocean during the peak of the Atlantic hurricane season.

# 8      Forthcoming Updated Forecasts of 2019 Hurricane Activity

We will be issuing seasonal updates of our 2019 Atlantic basin hurricane forecasts on **Tuesday 4 June**, **Tuesday 2 July, and Tuesday 6 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 2019 forecasts will be issued in late November 2019.  All of these forecasts will be available on our website.

# 9 Verification of Previous Forecasts

Table 12: Summary verification of the authors' five previous years of seasonal forecasts for Atlantic TC activity from 2014-2018.

| 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 | 14 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 | 27.75 |
| Named Storm Days | 52 | 53 | 55 | 55 | 81.00 |
| Major Hurricanes | 2 | 2 | 2 | 2 | 4 |
| Major Hurricane Days | 4 | 4 | 4 | 5 | 10.25 |
| Accumulated Cyclone Energy | 93 | 94 | 95 | 100 | 141 |
| Net Tropical Cyclone Activity | 101 | 103 | 105 | 110 | 155 |

| 2017 | 6 April | Update 1 June | Update 5 July | Update 4 August | Obs. |
|---|---|---|---|---|---|
| Hurricanes | 4 | 6 | 8 | 8 | 10 |
| Named Storms | 11 | 14 | 15 | 16 | 17 |
| Hurricane Days | 16 | 25 | 35 | 35 | 51.25 |
| Named Storm Days | 50 | 60 | 70 | 70 | 91.25 |
| Major Hurricanes | 2 | 2 | 3 | 3 | 6 |
| Major Hurricane Days | 4 | 5 | 7 | 7 | 19.25 |
| Accumulated Cyclone Energy | 75 | 100 | 135 | 135 | 226 |
| Net Tropical Cyclone Activity | 85 | 110 | 140 | 140 | 231 |

| 2018 | 5 April | Update 31 May | Update 2 July | Update 2 August | Obs. |
|---|---|---|---|---|---|
| Hurricanes | 7 | 6 | 4 | 5 | 8 |
| Named Storms | 14 | 14 | 11 | 12 | 15 |
| Hurricane Days | 30 | 20 | 15 | 15 | 26.75 |
| Named Storm Days | 70 | 55 | 45 | 53 | 87.25 |
| Major Hurricanes | 3 | 2 | 1 | 1 | 2 |
| Major Hurricane Days | 7 | 4 | 2 | 2 | 5.00 |
| Accumulated Cyclone Energy | 130 | 90 | 60 | 64 | 129 |
| Net Tropical Cyclone Activity | 135 | 100 | 70 | 78 | 128 |