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

We have increased our forecast slightly and now believe that 2019 will have approximately average activity. There remains considerable uncertainty as to whether El Niño conditions will persist through the Atlantic hurricane season. The tropical Atlantic has warmed slightly faster than normal over the past few weeks and now has near-average sea surface temperatures. We anticipate a near-average probability for major hurricanes making landfall along the United States coastline and in the Caribbean. As is the case with all hurricane seasons, coastal residents are reminded that it only takes one hurricane making landfall to make it an active season for them. They should prepare the same for every season, regardless of how much activity is predicted.

(as of 4 June 2019)

By Philip J. Klotzbach[1], Michael M. Bell[2], and Jhordanne Jones[3]

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	Issue Date 4 June 2019	Observed Activity Through May 2019	Total Seasonal Forecast (Including Andrea*)
Named Storms (NS) (12.1)	13	13	1	14
Named Storm Days (NSD) (59.4)	50	54.25	0.75	55
Hurricanes (H) (6.4)	5	6	0	6
Hurricane Days (HD) (24.2)	16	20	0	20
Major Hurricanes (MH) (2.7)	2	2	0	2
Major Hurricane Days (MHD) (6.2)	4	5	0	5
Accumulated Cyclone Energy (ACE) (106)	80	99	1	100
Net Tropical Cyclone Activity (NTC) (116%)	90	102	3	105

*Subtropical Storm Andrea formed prior to the official start of the Atlantic hurricane season on June 1.

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 – 54% (average for last century is 52%)

2) U.S. East Coast Including Peninsula Florida – 32% (average for last century is 31%)

3) Gulf Coast from the Florida Panhandle westward to Brownsville - 31% (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) 44% (average for last century is 42%)

ABSTRACT

Information obtained through May 2019 indicates that the 2019 Atlantic hurricane season will have activity near the the 1981-2010 average. This is a slight increase in our forecast from early April. We estimate that 2019 will have about 6 hurricanes (average is 6.4), 14 named storms (average is 12.1), 55 named storm days (average is 59.4), 20 hurricane days (average is 24.2), 2 major (Category 3-4-5) hurricanes (average is 2.7) and 5 major hurricane days (average is 6.2). These numbers include Subtropical Storm Andrea which formed in May. The probability of U.S. major hurricane landfall is estimated to be near the 20th century average. We expect Atlantic basin Accumulated Cyclone Energy (ACE) and Net Tropical Cyclone (NTC) activity in 2019 to be approximately 95 percent of their 1981-2010 averages.

This forecast is based on an extended-range early June statistical prediction scheme that was developed using 29 years of past data. Analog predictors are also utilized. For the first time this year, we are also using a statistical/dynamical model based off of data from the ECMWF SEA5 as an additional forecast guidance tool.

There remains considerable uncertainty as to the state of ENSO for this summer/fall. We currently anticipate that current weak El Niño event conditions will persist, but some anomalous cooling in recent weeks weakens our confidence in this assessment. The tropical Atlantic has undergone slight anomalous warming and is now characterized by near-average sea surface temperatures. The subtropical Atlantic remains quite warm, while 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 thermohaline circulation is weaker. A weaker thermohaline circulation is typically associated with a negative phase of the Atlantic Multi-decadal Oscillation. 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 June forecast has shown moderate long-term skill when evaluated in hindcast mode. Updates issued in early July and early August show higher levels of skill, as they are issued closer to the peak of the Atlantic hurricane season (August-October).

Why issue extended-range forecasts for seasonal hurricane activity?

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

Everyone should realize that it is impossible to precisely predict this season's hurricane activity in early June. There is, however, much curiosity as to how global ocean and atmosphere features are presently arranged as regards to the probability of an active or inactive hurricane season for the coming year. Our early June statistical 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

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 in 2016. 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, Ironshore Insurance, the Insurance Information Institute and Weatherboy 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, Louis-Philippe Caron, Brian McNoldy, Paul Roundy, Jason Dunion, Peng Xian 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 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 June 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 June Forecast Methodology

2.1 June Statistical Forecast Scheme

Our current June statistical forecast model was built over the period from 1982-2010 to incorporate more recent data where a denser observational network was available. It uses a total of four predictors. The Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) has been completed from 1979-2010, with a continuation of

CFS version 2 data through until present, while the NOAA Optimum Interpolation (OI) SST (Reynolds et al. 2002) is available from 1982-present. This 1 June TC forecast model shows significant skill in predicting levels of Accumulated Cyclone Energy (ACE) activity over the 37-year period from 1982-2018. This hindcast model correlates with ACE at 0.73 during this period. We do note that the model has under-predicted hurricane activity over the past three years. In each of these seasons, the atmosphere/ocean system trended more hurricane-favorable during the peak of the season than what was observed at the start of the season.

Figure 2 displays the locations of each of our predictors, while Table 1 displays the individual linear correlations between each predictor and ACE from 1982-2018. All predictors correlate significantly at the 95% level using a two-tailed Student's t-test. We are incorporating a dynamical SST forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF). Hindcast data provided by Frederic Vitart indicates that the ECMWF model has significant forecast skill for SSTs across the various Nino regions for September from a 1 May forecast date. We utilize the ECMWF ensemble mean prediction for September Nino 3 SSTs. Table 2 displays the 2019 observed values for each of the four predictors in the new statistical forecast scheme. The combination of the four predictors calls for a near-average season. Three of the predictors are near their long-term average values, while predictor 4 is strongly favorable for an active season. Table 3 displays the statistical model output for the combination of the four predictors for the 2019 Atlantic hurricane season.

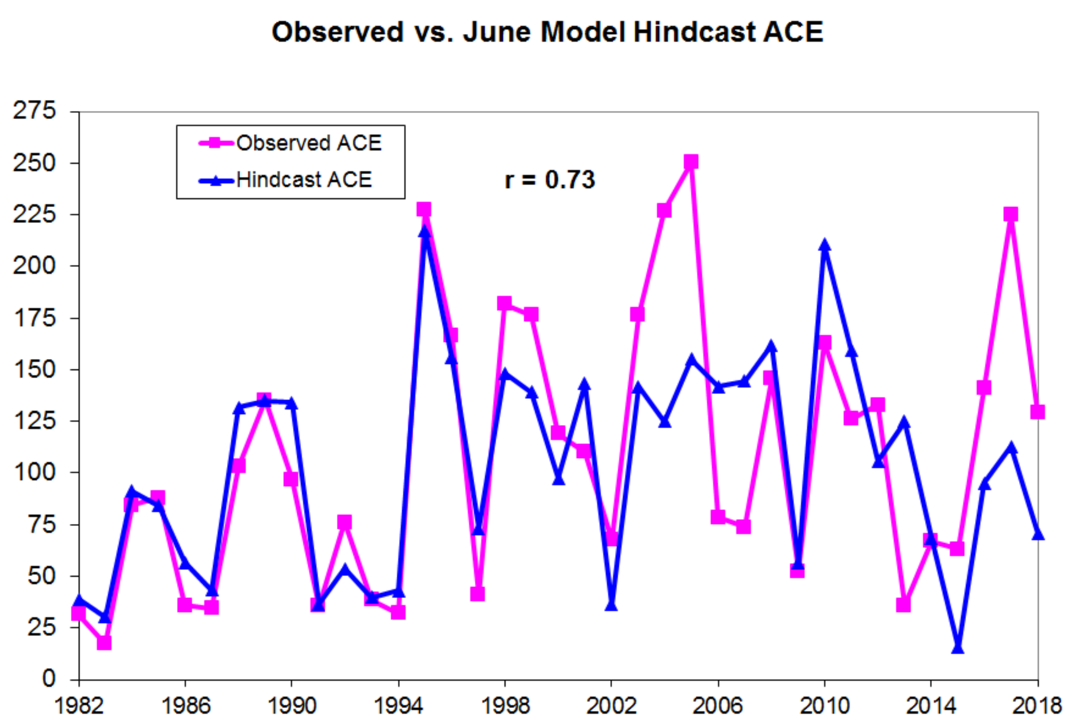

Figure 1: Observed versus early June hindcast values of ACE for 1982-2018.

June Forecast Predictors

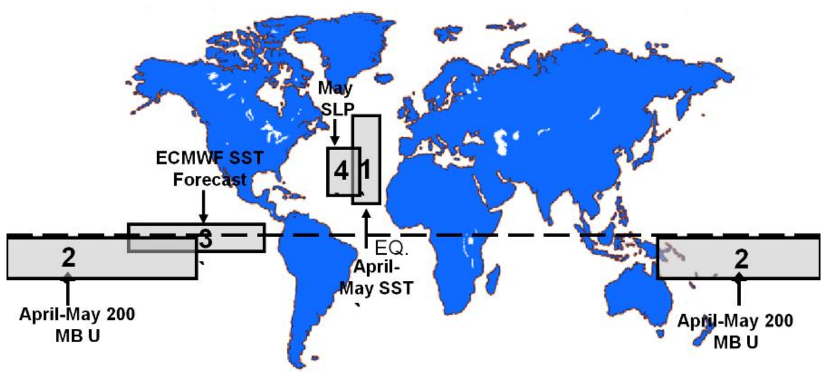

Figure 2: Location of predictors for our early June extended-range statistical prediction for the 2019 hurricane season. Predictor 2 spans both sides of the International Date Line.

Table 1: Linear correlation between each 1 June predictor and ACE from 1982-2018. For more ACE activity, the sign of predictors 1 and 2 should be positive, while the sign of predictors 3 and 4 should be negative.

Predictor	**Correlation w/ ACE**
1) April-May SST (15-55°N, 15-35°W) (+)	0.55
2) April-May 200 MB U (0-15°S, 150°E-120°W) (+)	0.46
3) ECMWF 1 May SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	-0.41
4) May SLP (20-40°N, 30-50°W) (-)	-0.42

Table 2: Listing of 1 June 2019 predictors for the 2019 hurricane season. A plus (+) means that positive values of the parameter indicate increased hurricane activity. The combination of the four predictors calls for a near-average Atlantic hurricane season. SD stands for standard deviations.

Predictor	**2019 Forecast Value**
1) April-May SST (15-55°N, 15-35°W) (+)	-0.2 SD
2) April-May 200 MB U (0-15°S, 150°E-120°W) (+)	-0.1 SD
3) ECMWF 1 May SST Forecast for September Nino 3 (5°S-5°N, 90-150°W) (-)	+0.4 SD
4) May SLP (20-40°N, 30-50°W) (-)	-1.6 SD

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)	11.8	14
Named Storm Days (NSD) (59.4)	60.8	55
Hurricanes (H) (6.4)	6.9	6
Hurricane Days (HD) (24.2)	28.4	20
Major Hurricanes (MH) (2.7)	3.2	2
Major Hurricane Days (MHD) (6.2)	7.7	5
Accumulated Cyclone Energy (ACE) (106)	118	100
Net Tropical Cyclone Activity (NTC) (116%)	128	105

2.2 Physical Associations among Predictors Listed in Table 1

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

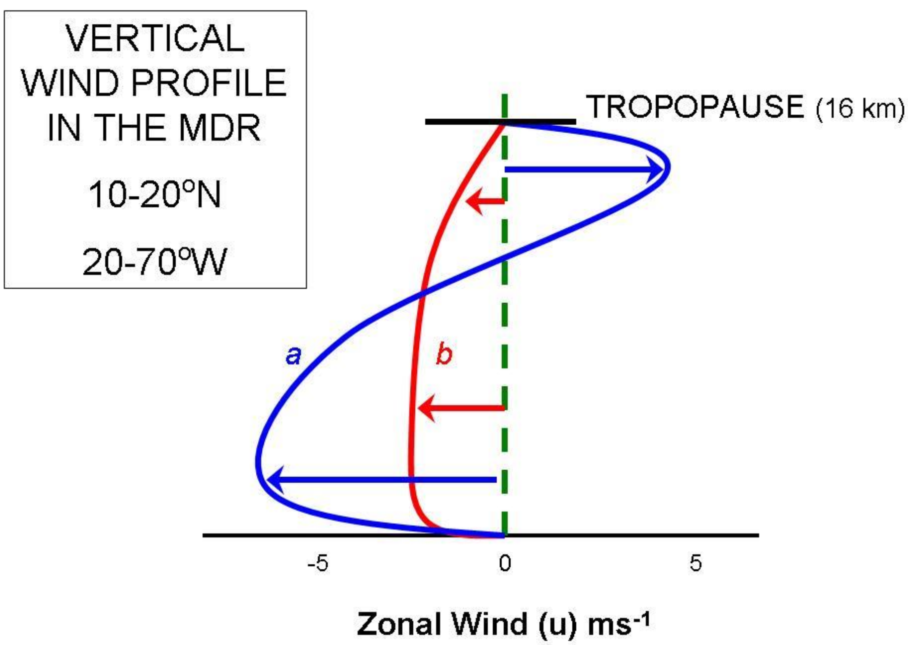

Figure 3: Vertical wind profile typically associated with (a) inactive Atlantic basin hurricane seasons and (b) active Atlantic basin hurricane seasons. Note that (b) has reduced levels of tropospheric vertical wind shear.

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

<u>Predictor 1. April-May SST in the Eastern Atlantic (+)</u>

(15-55°N, 15-35°W)

Warmer-than-normal SSTs in the eastern Atlantic during the April-May period are associated with a weaker-than-normal subtropical high and reduced trade wind strength during the boreal spring (Knaff 1997). Positive SST anomalies in April-May are correlated with weaker trade winds and weaker upper tropospheric westerly winds, lower-than-normal sea level pressures and above-normal SSTs in the tropical Atlantic during the following August-October period (Figure 4). All three of these August-October features are commonly associated with active Atlantic basin hurricane seasons, through reductions in vertical wind shear, increased vertical instability and increased mid-tropospheric moisture, respectively. Predictor 1 correlates quite strongly (~0.55) 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.

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

(0-15°S, 150°E-120°W)

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

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

(5°S -5°N, 90-150°W)

The ECMWF seasonal forecast system 3 has shown skill at being able to forecast SST anomalies associated with ENSO several months into the future (Stockdale et al. 2011). ECMWF has since upgraded their seasonal forecast model to SEA5. ENSO has been documented in many studies to be one of the primary factors associated with interannual fluctuations in Atlantic basin and U.S. landfalling hurricane activity (Gray 1984, Goldenberg and Shapiro 1996, Bove et al. 1998, Klotzbach 2011), primarily through alterations in vertical wind shear patterns. The ensemble-averaged ENSO forecast for September values of the Nino 3 region from a 1 May issue date correlates with observations at 0.81. When the ECMWF model predicts cool SST anomalies for September, it strongly correlates with observed cool anomalies throughout the tropical Pacific associated with La Niña conditions, as well as reduced vertical wind shear, especially across the Caribbean (Figure 6).

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

(20-40°N, 30-50°W)

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

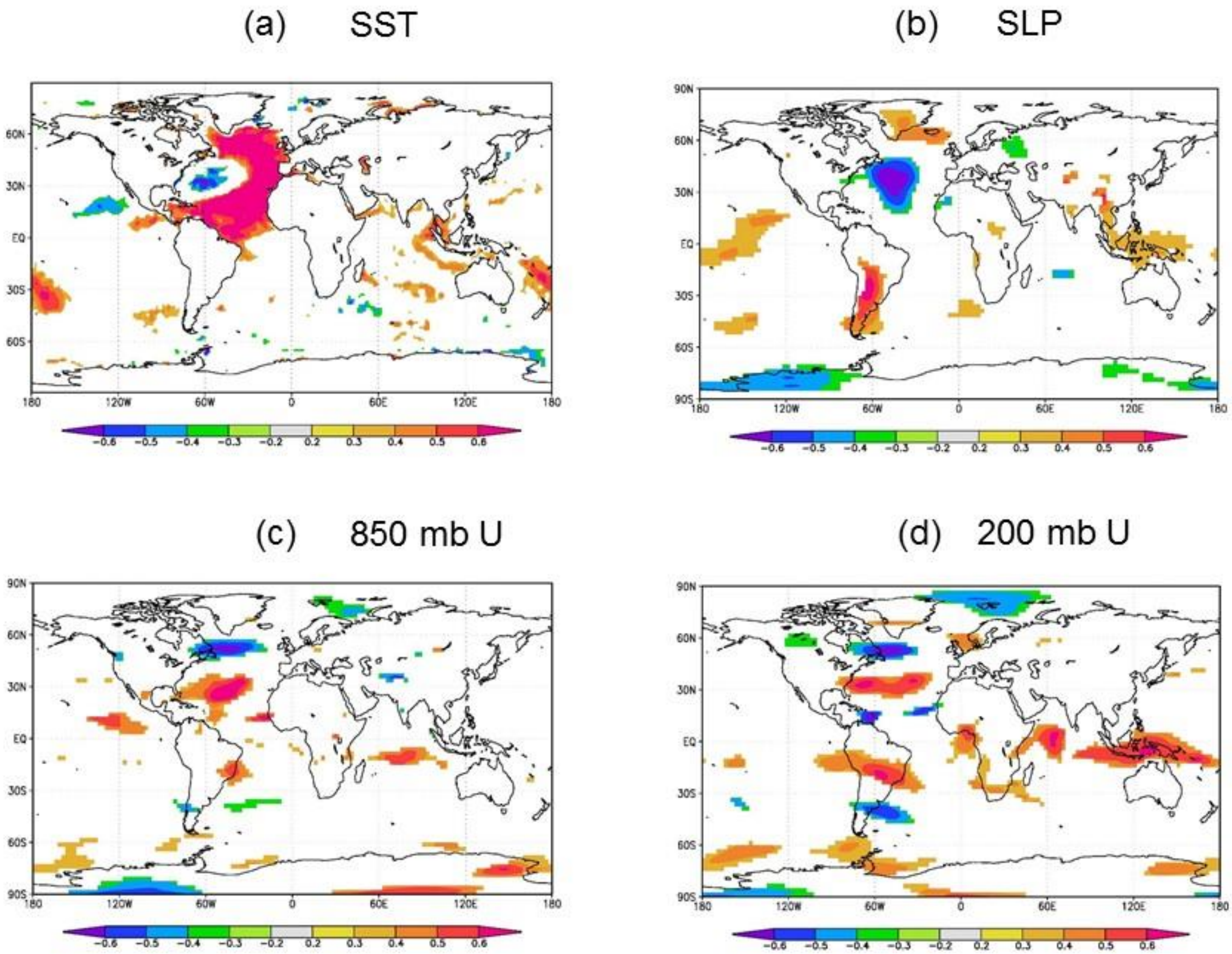

Figure 4: Linear correlations between April-May SST in the eastern Atlantic (Predictor 1) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following August-October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

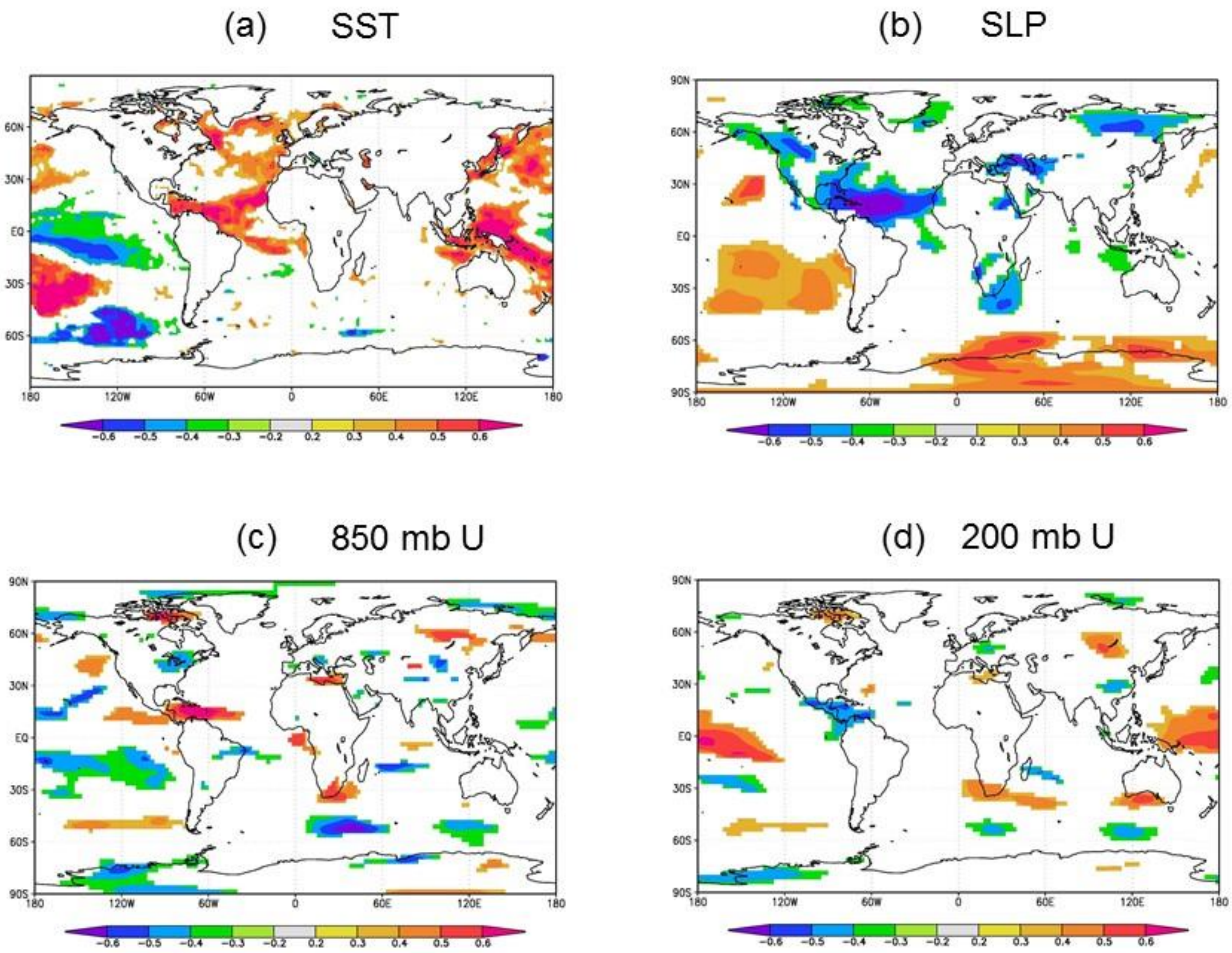

Figure 5: Linear correlations between April-May 200-mb zonal winds in the south-central tropical Pacific (Predictor 2) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c)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

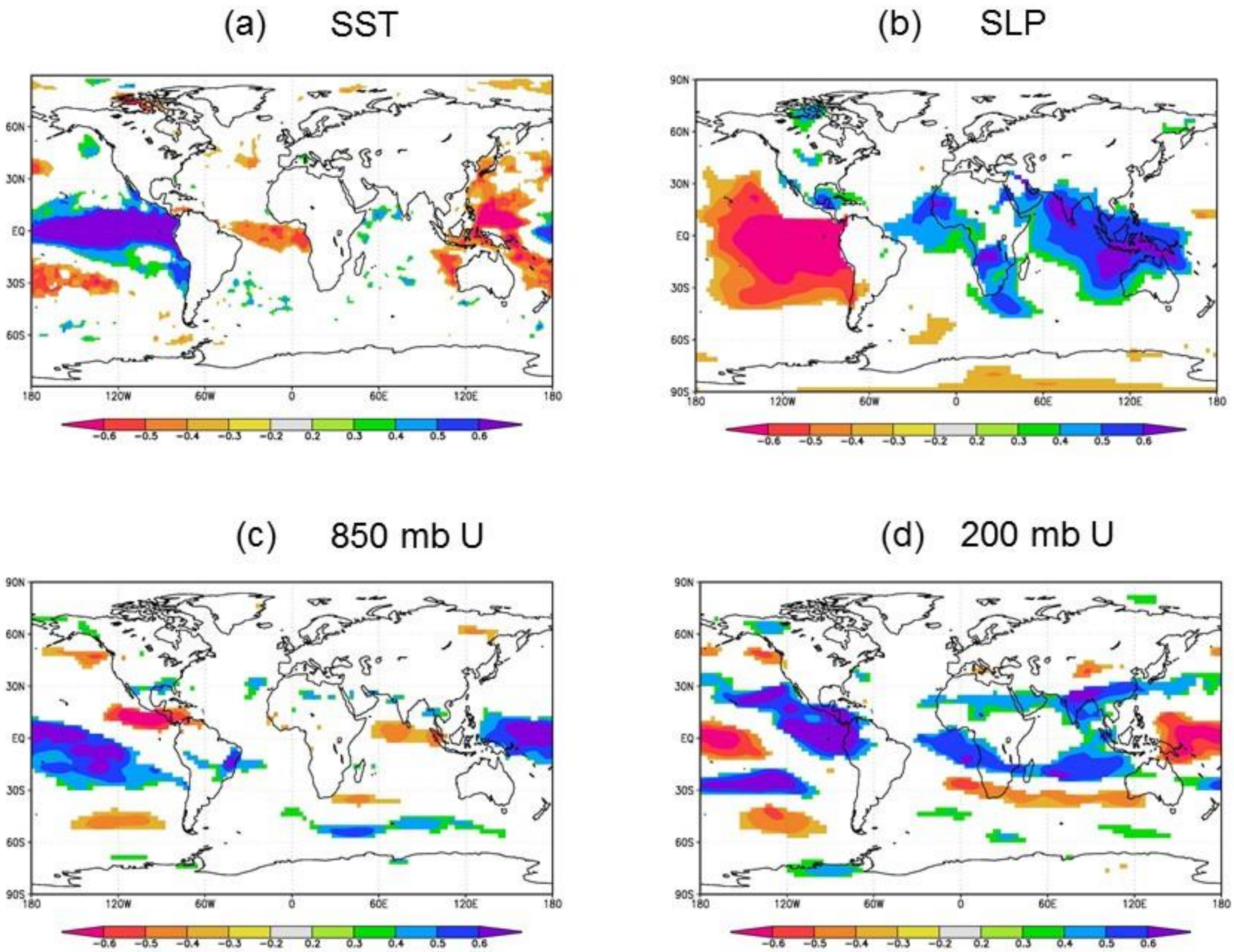

Figure 6: Linear correlations between a 1 May ECMWF SST forecast for September Nino 3 (Predictor 3) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following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

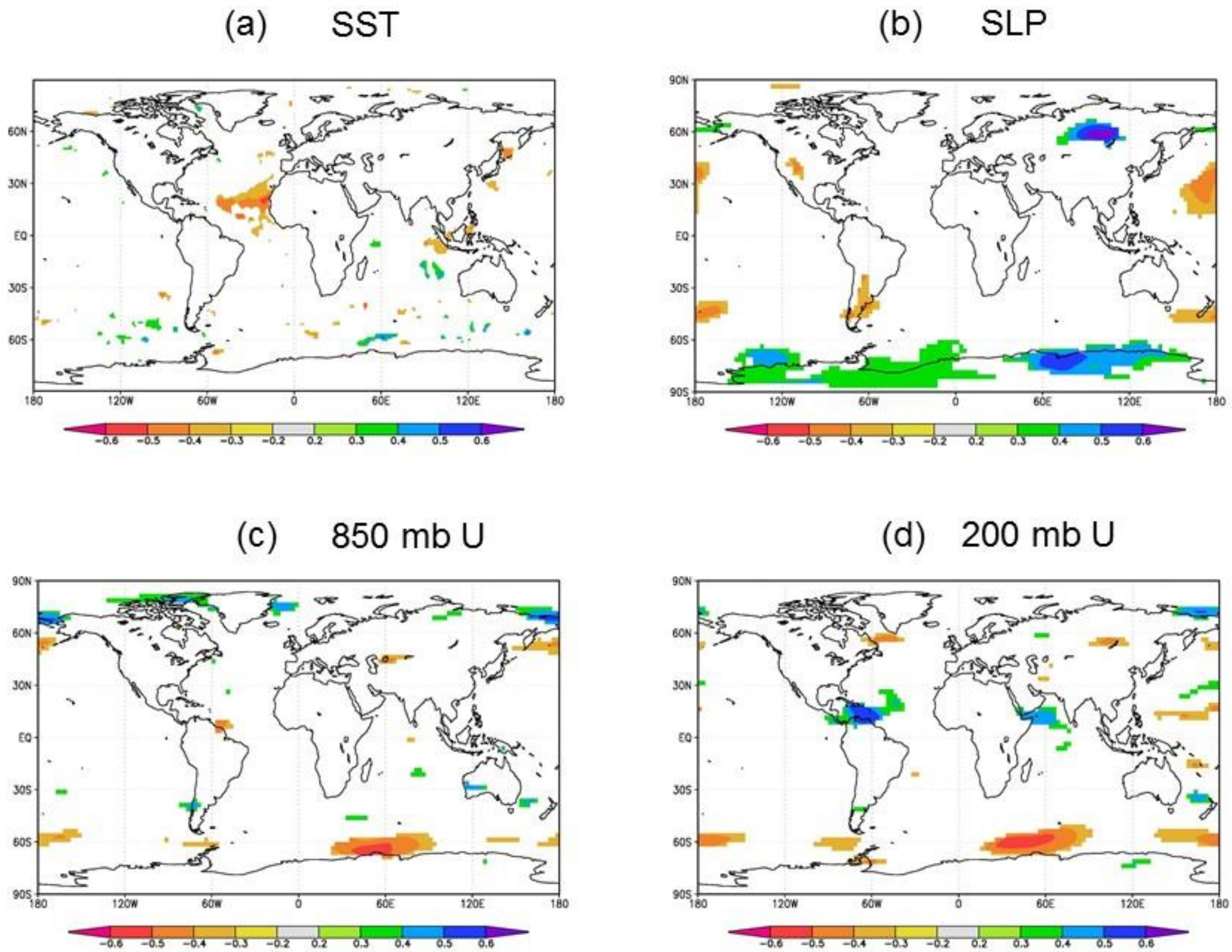

Figure 7: Linear correlations between May sea level pressure in the central Atlantic (Predictor 4) and the following August-October sea surface temperature (panel a), the following August-October sea level pressure (panel b), the following August-October 850 mb zonal wind (panel c) and the following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

2.3 June 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 SEA5 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 SEA5 is able to forecast the large-scale fields that go into the early August statistical forecast model with considerable skill by March. This skill then improves as the peak of the hurricane season approaches. 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 SEA5 output, so the results displayed below are from the model output from the 1 May forecast.

Figure 8 displays the parameters used in our early August statistical model, while Table 4 displays SEA5's forecasts of these parameters for 2019. SEA5 is calling for above-average trade wind strength, which is typically associated with quieter Atlantic hurricane seasons. However, the model is also calling for above-normal 2-meter temperatures in the eastern subtropical Atlantic and near-normal zonal wind over western tropical Africa. Predictors 2 and 3 are weighed stronger in the May model than is trade wind strength. Figure 9 displays hindcast data of the SEA5 forecast of ACE from 1981-2018. Table 5 presents the forecast from SEA5, which calls for an average season.

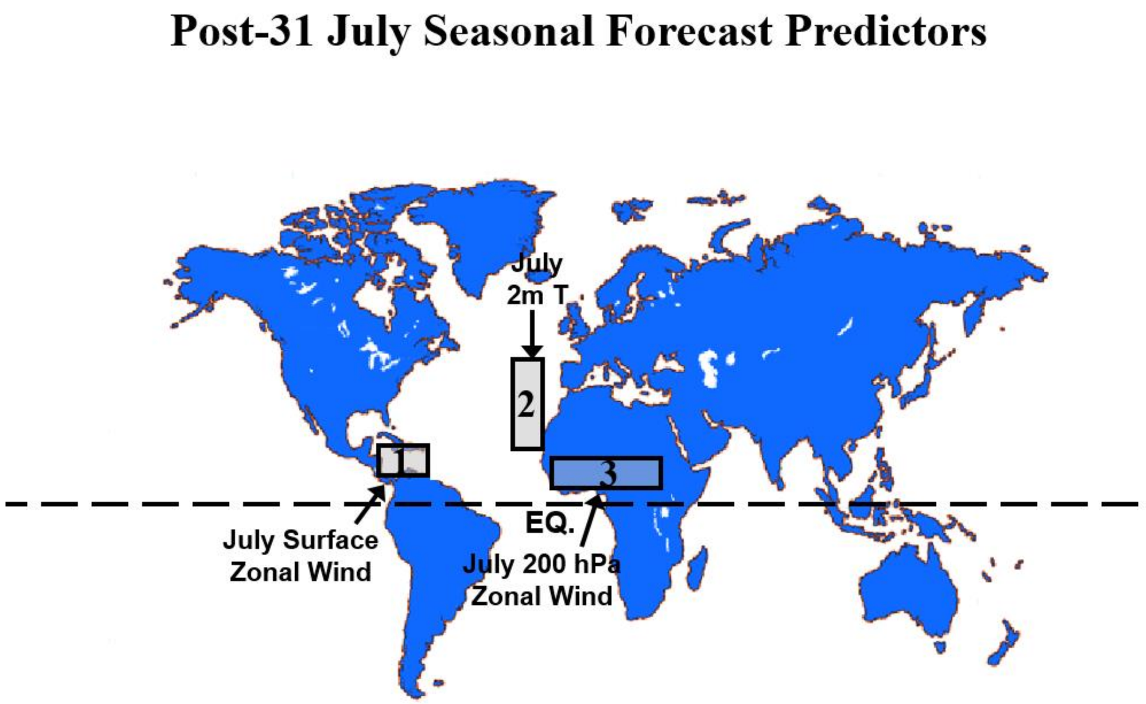

Figure 8: Location of predictors for our August statistical/dynamical extended-range statistical prediction for the 2019 hurricane season. This forecast uses ECMWF SEA5 to predict July conditions in the three boxes displayed and uses those predictors to forecast ACE.

Table 4: Listing of predictions of July large-scale conditions from ECMWF SEA5 output, initialized on 1 May. 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) SEA5 Prediction of July Surface U (10-17.5°N, 60-85°W) (+)	-1.2 SD	Suppress
2) SEA5 Prediction of July 2-Meter Temperature (20-40°N, 15-35°W) (+)	+0.4 SD	Enhance
3) SEA5 Prediction of July 200 mb U (5-15°N, 0-40°E) (-)	+0.2 SD	Suppress

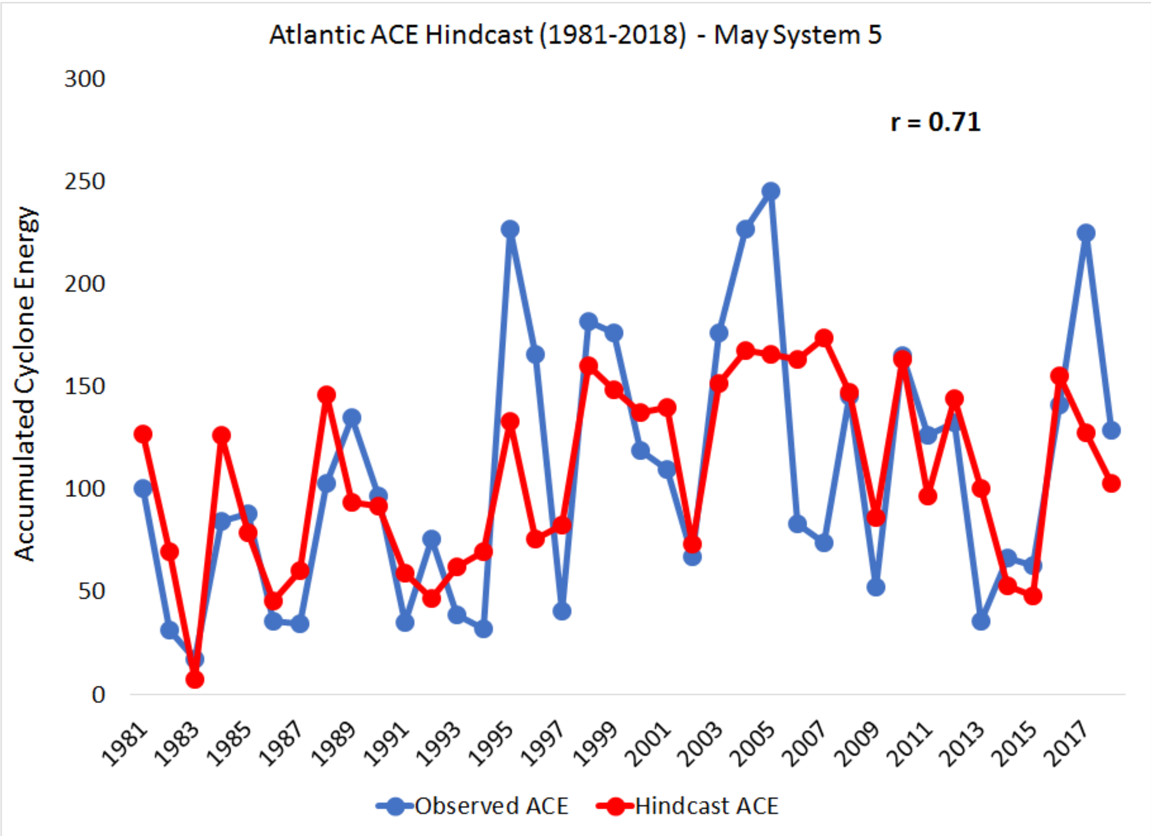

Figure 9: Observed versus hindcast ACE values using the statistical/dynamical hybrid model, initialized on 1 May.

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)	11.2	14
Named Storm Days (59.4)	56.5	55
Hurricanes (6.4)	6.5	6
Hurricane Days (24.2)	25.9	20
Major Hurricanes (2.7)	2.8	2
Major Hurricane Days (6.2)	6.8	5
Accumulated Cyclone Energy Index (106)	108	100
Net Tropical Cyclone Activity (116%)	117	105

2.4 June 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 June extended range forecast, we determine which of the prior years in our database have distinct trends in key environmental conditions which are similar to current April-May 2019 conditions as well as projected August-October 2019 conditions. Table 6 lists our analog selections.

We searched for years that were generally characterized by weak El Niño conditions and near-average SSTs in the tropical Atlantic during August-October. 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
1990	14	72.25	8	26.75	1	1.00	97	100
1991	8	24.25	4	8.25	2	1.25	36	58
2012	19	101.25	10	28.50	2	0.50	133	131
2014	8	35.00	6	17.75	2	3.75	67	82
2018	15	86.75	8	27.50	2	5.25	133	129
Average	12.8	63.9	7.2	21.8	1.8	2.4	93	99
2019 Forecast	**14**	**55**	**6**	**20**	**2**	**5**	**100**	**105**

2.5 June Forecast Summary and Final Adjusted Forecast

Table 7 shows our final adjusted early June 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. All three schemes call for near-average activity. Our forecast is close to the average of the three schemes and also calls for a near-average season, due to what we anticipate will be weak El Niño conditions and near-average tropical Atlantic SST conditions for the peak of the Atlantic hurricane season (August-October).

Table 7: Summary of our early June 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)	11.8	11.2	12.8	11.9	14
Named Storm Days (59.4)	60.8	56.5	63.9	60.4	55
Hurricanes (6.4)	6.9	6.5	7.2	6.9	6
Hurricane Days (24.2)	28.4	25.9	21.8	25.4	20
Major Hurricanes (2.7)	3.2	2.8	1.8	2.6	2
Major Hurricane Days (6.2)	7.7	6.8	2.4	5.6	5
Accumulated Cyclone Energy Index (106)	118	108	93	106	100
Net Tropical Cyclone Activity (116%)	128	117	99	115	105

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. While the uncertainty with the June forecast is less than the April forecast, there is still considerable uncertainty in the state of ENSO as well as the Atlantic basin SST configuration for the peak of the Atlantic hurricane season.

Table 8 provides our early June 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.

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)	4	14	10 – 18
Named Storm Days (NSD)	21	55	34 – 76
Hurricanes (H)	2	6	4 – 8
Hurricane Days (HD)	10	20	10 – 30
Major Hurricanes (MH)	1	2	1 – 3
Major Hurricane Days (MHD)	4	5	1 – 9
Accumulated Cyclone Energy (ACE)	48	100	52 – 148
Net Tropical Cyclone (NTC) Activity	48	105	57 – 153

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. From October through December, SST anomalies increased, and the tropical Pacific was characterized by weak El Niño conditions (Nino 3.4 between 0.5°C – 1.0°C). There was some anomalous cooling from December to February, followed by anomalous warming from February to March. There was then a gradual anomalous cooling until the past couple of weeks, where a rapid anomalous warming has ensued.

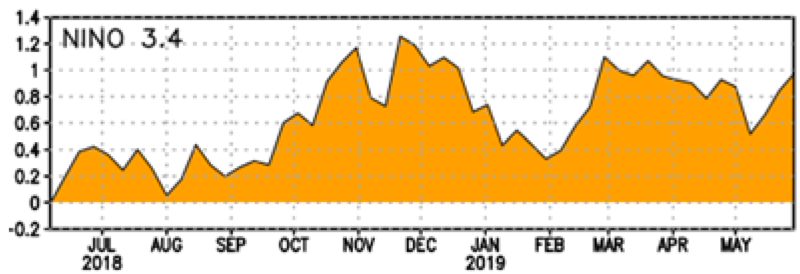

Figure 10: Nino 3.4 SST anomalies from June 2018 through May 2019. Figure courtesy of Climate Prediction Center.

Upper-ocean heat content anomalies in the eastern and central tropical Pacific were at above-normal levels from last spring through this 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 again increased in February and March. There was pronounced upper ocean cooling from late March through mid-May, where ocean heat content anomalies dropped below normal. Over the past couple of weeks, upper ocean heat content anomalies have again begun to increase, associated with a downwelling Kelvin wave that is currently developing.

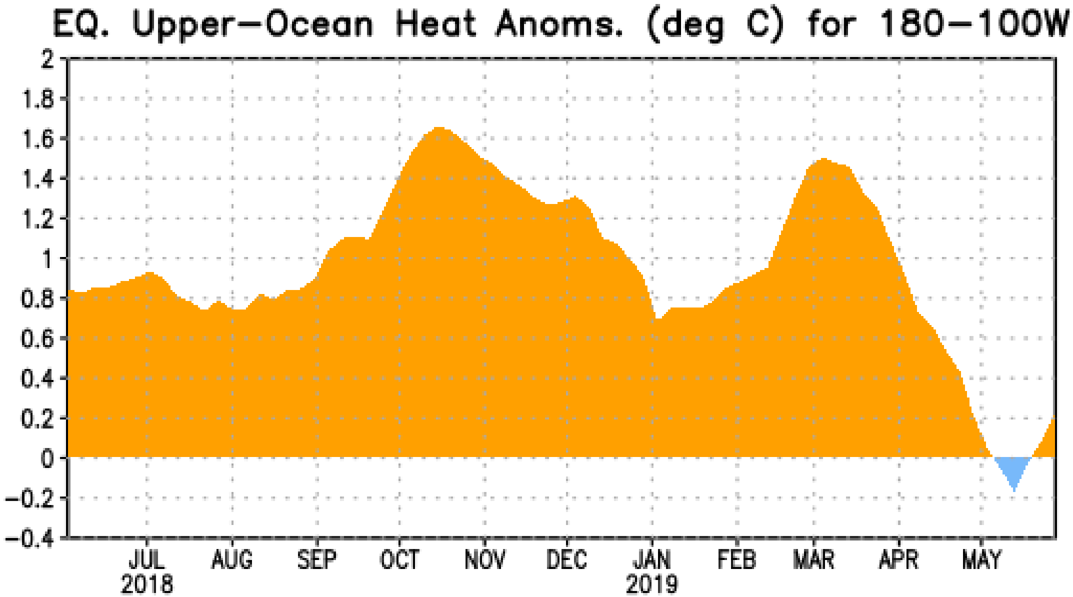

Figure 11: Central and eastern equatorial Pacific upper ocean (0-300 meters) heat content anomalies over the past year. Upper ocean heat content anomalies decreased from mid-March to mid-May, with a recent slight increase.

SSTs are above normal across the entire tropical Pacific (Figure 12). These anomalies are generally between 0.5°C and 1.0°C above average in the eastern and central tropical Pacific, indicative of the weak El Niño that is currently in place.

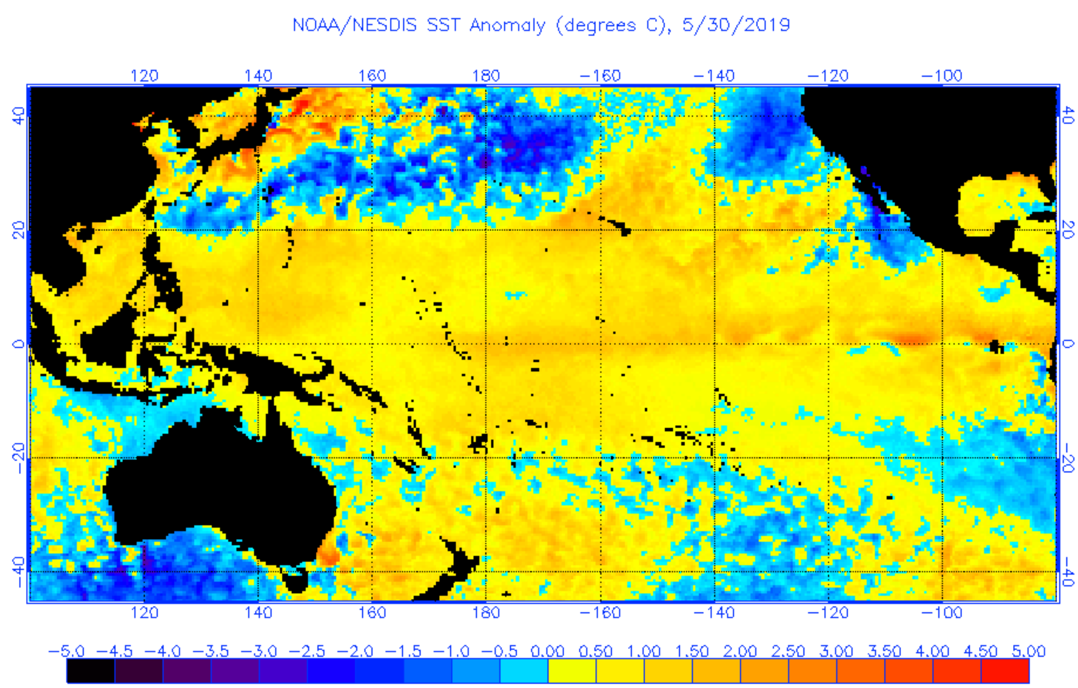

Figure 12: Current SST anomalies across the tropical and subtropical Pacific.

Table 9 displays March and May SST anomalies for several Nino regions. Anomalies have trended slightly downward over the past couple of months across the central tropical Pacific, with slight anomalous warming in the eastern tropical Pacific. There remains considerable uncertainty as to whether the weak El Niño will persist for the next several months.

Table 9: March and May SST anomalies for Nino 1+2, Nino 3, Nino 3.4, and Nino 4, respectively. May minus March SST anomaly differences are also provided.

Region	March SST Anomaly (°C)	May SST Anomaly (°C)	May – March SST Anomaly (°C)
Nino 1+2	+0.2	+0.3	+0.1
Nino 3	+0.8	+0.6	-0.2
Nino 3.4	+1.0	+0.8	-0.2
Nino 4	+0.9	+0.8	-0.1

The tropical Pacific experienced a downwelling (warming) Kelvin wave (denoted by the long dashed line) that caused anomalous warming across the tropical Pacific in February and March (Figure 13). There was then an upwelling (cooling) Kelvin wave that caused anomalous cooling across the tropical Pacific during April and most of May. However, over the past couple of weeks, a very strong westerly wind burst has developed over the western and central tropical Pacific (Figure 14). While this westerly wind burst has started weakening, the latest outlook from the Climate Forecast System (CFS) model calls for a continuation of anomalous low-level westerly flow near the date line. This should help prevent a rapid transition away from El Niño conditions.

While increases in upper ocean heat content anomalies are only just becoming visible in Figure 13, a stronger signal is seen when examining data from the TAO/TRITON buoy area across the tropical Pacific. Large increases in both dynamic height as well as upper-ocean heat content can be seen in the central tropical Pacific, likely harbingers of a robust downwelling Kelvin wave taking shape (Figure 15).

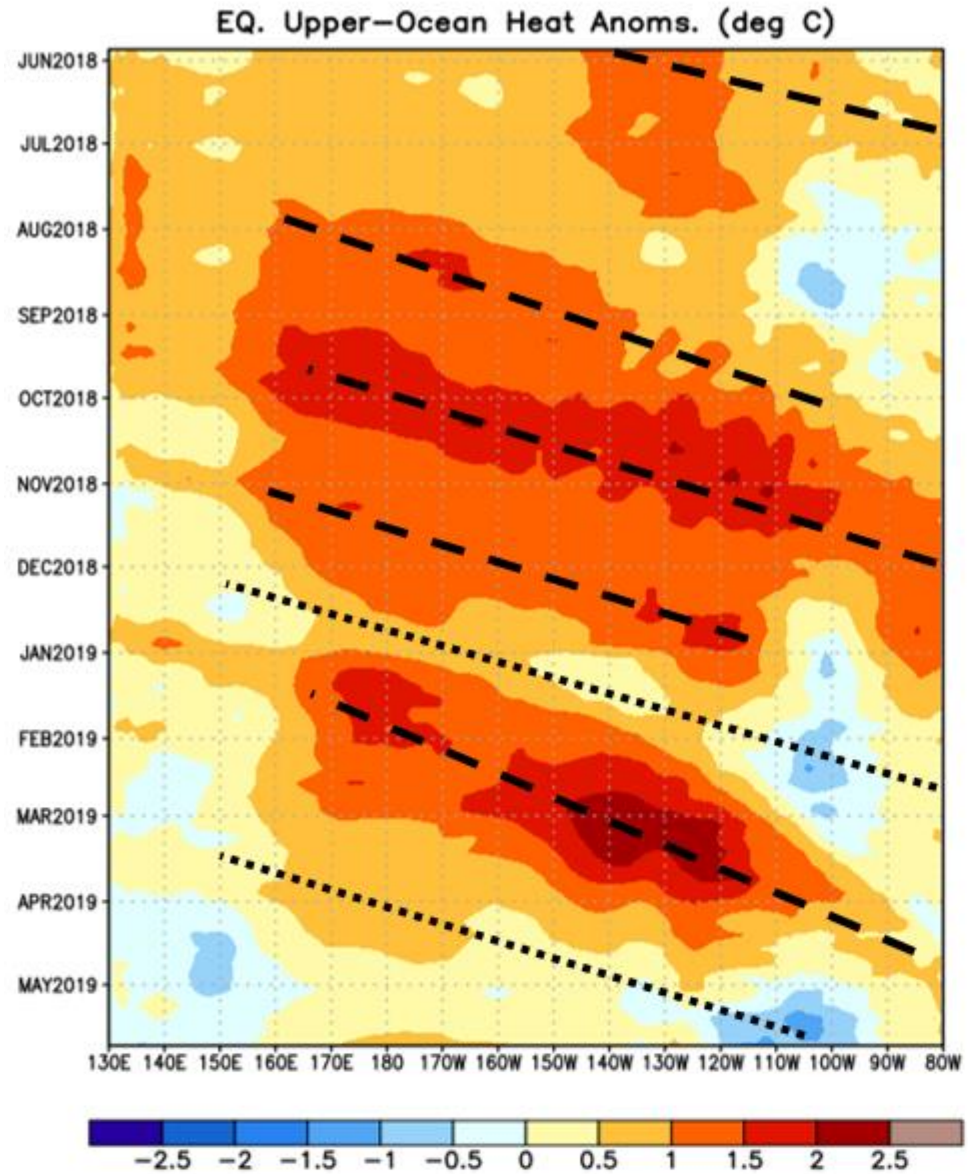

Figure 13: Upper-ocean heat content anomalies in the tropical Pacific since June 2018. Dashed lines indicate downwelling Kelvin waves, while dotted lines indicate upwelling Kelvin waves. Downwelling Kelvin waves result in upper-ocean heat content increases, while upwelling Kelvin waves recent in upper-ocean heat content decreases.

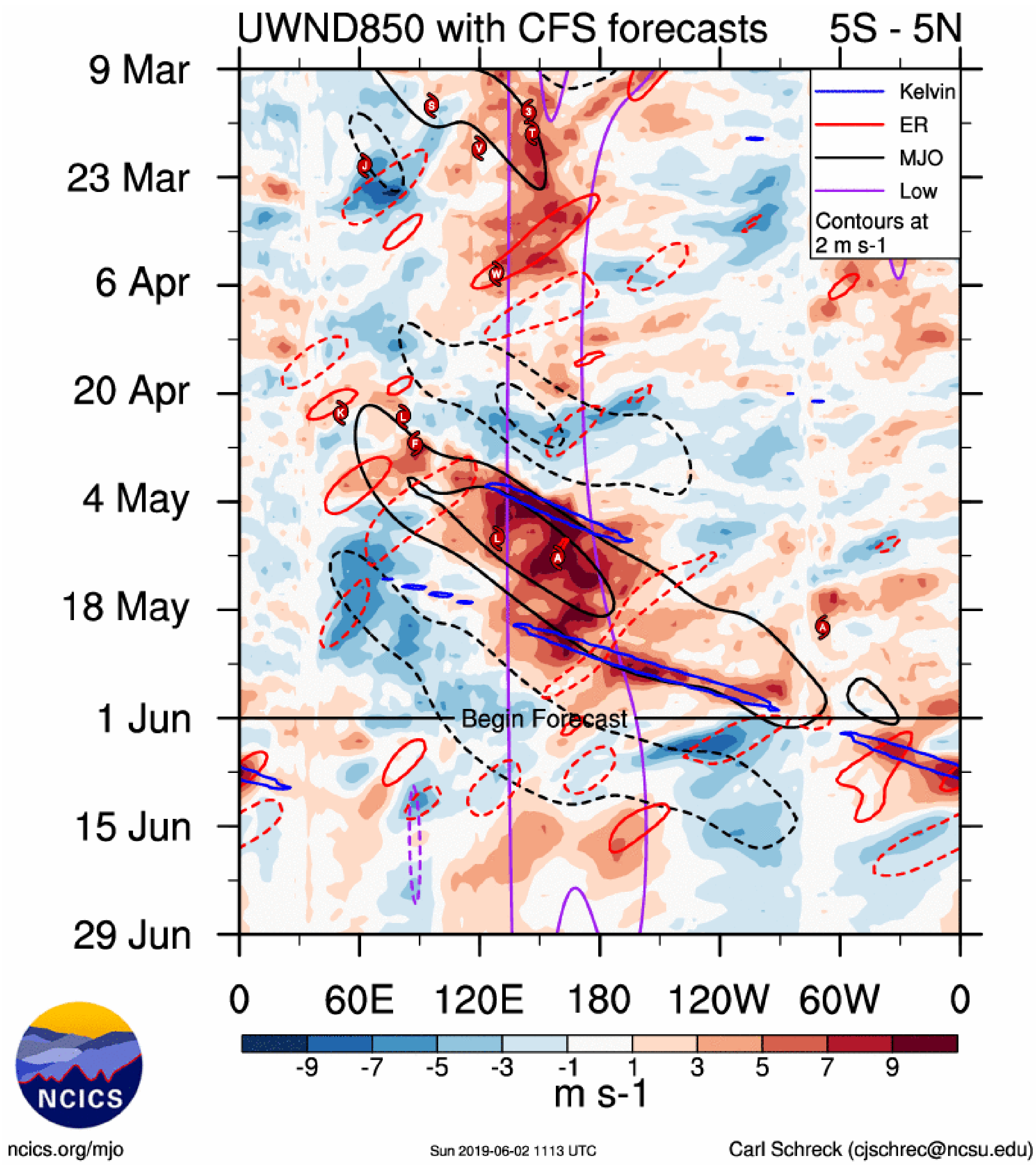

Figure 14: Observed low-level winds across the equatorial region as well as predictions for the next four weeks by the Climate Forecast System. Figure courtesy of Carl Schreck.

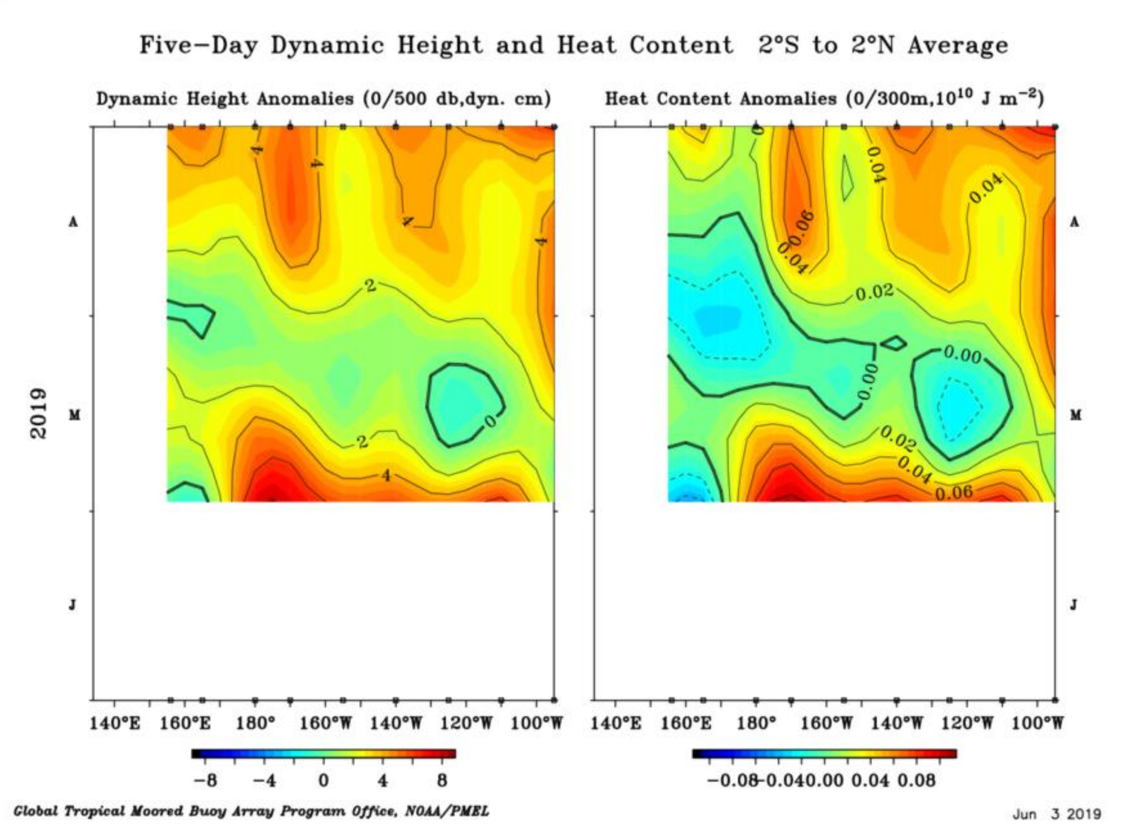

Figure 15: Dynamic height anomalies and ocean heat content anomalies averaged across the tropical Pacific from April 1 to May 29. Both dynamic height anomalies and ocean heat content anomalies have shown large increases near the International Date Line over the past couple of weeks.

There remains considerable uncertainty with the future state of El Niño. The latest plume of ENSO predictions from several statistical and dynamical models continues to show 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.

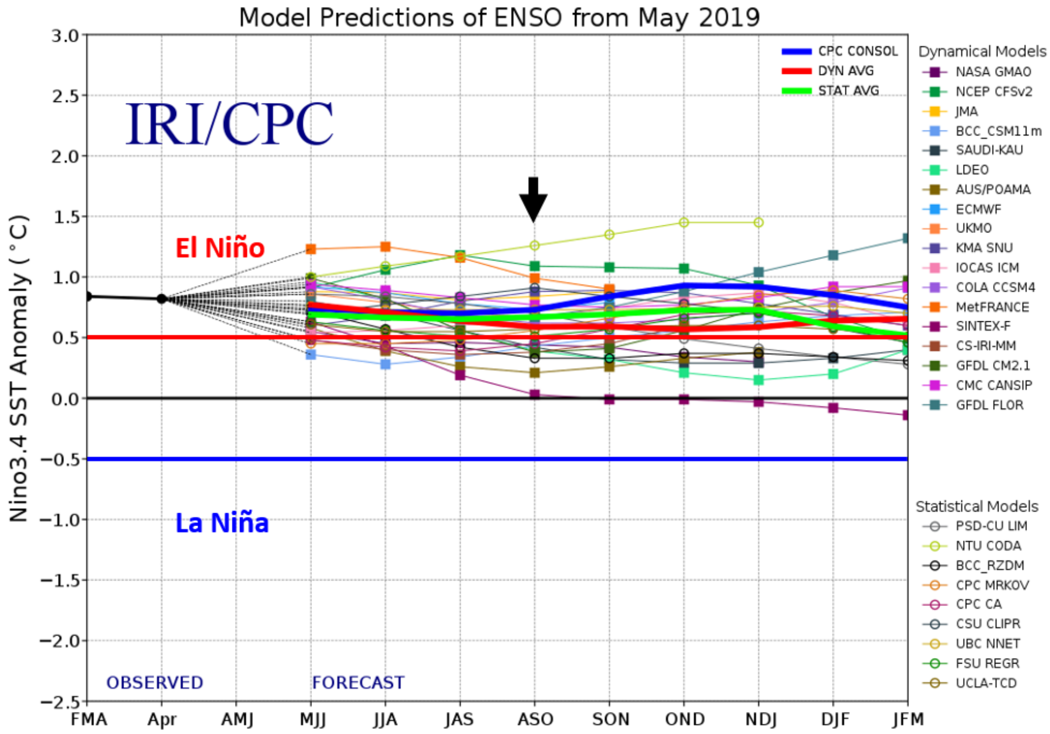

Figure 16: ENSO forecasts from various statistical and dynamical models for the Nino 3.4 SST anomaly based on late April to early May initial conditions. About 2/3 of all forecast models are calling for El Niño conditions to persist through August-October (black arrow), which is the climatological peak 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. While we are nearing the end of the springtime predictability barrier, there remains considerable uncertainty with ENSO forecasts initialized in early May (as the most recent ECMWF forecast was).

The average of the various ECMWF ensemble members is calling for a September Nino 3.4 SST anomaly of approximately +0.4°C. There is a fairly wide spread for the range of outcomes predicted by the various ensemble members, which highlights the large degree of uncertainty in future ENSO conditions (Figure 17). Approximately half of the ECMWF ensemble members are calling for El Niño conditions to persist through September.

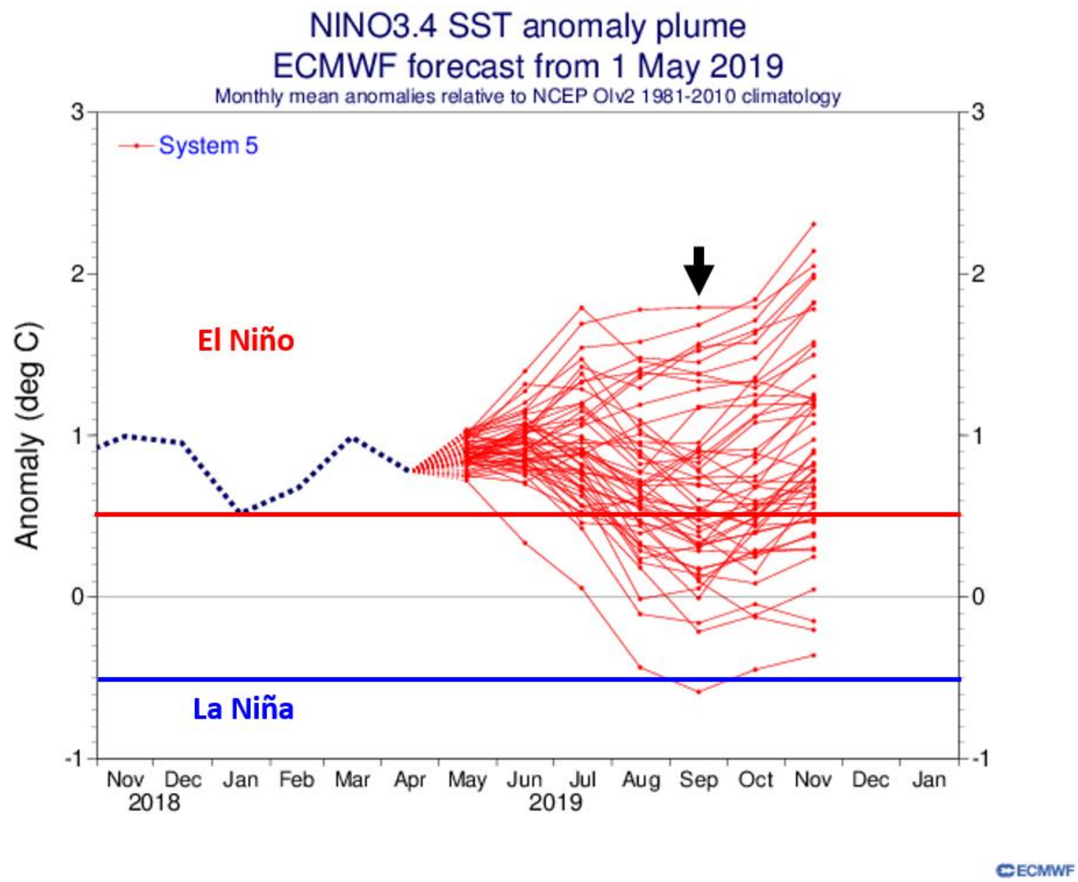

Figure 17: ECMWF ensemble model forecast for the Nino 3.4 region. About 50% of ensemble members are calling for continued El Niño conditions through September.

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. We will continue to monitor future changes in ENSO and will have more to say with our forecast updates issued in early July and early August.

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 near average SST anomalies in the tropical Atlantic (Figure 18).

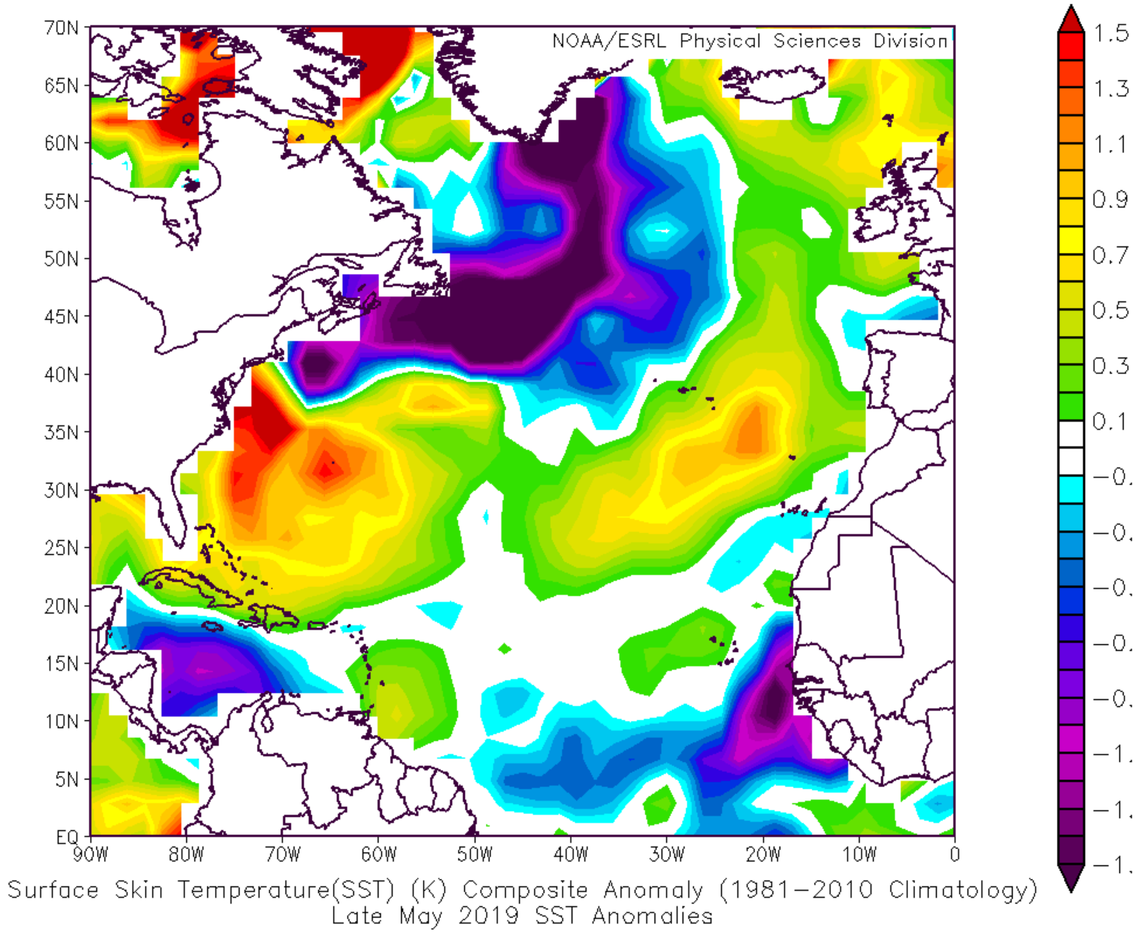

Figure 18: Late May 2019 SST anomaly pattern across the Atlantic Ocean.

In general, SSTs in portions of the far North Atlantic have anomalously warmed since late April, while SSTs off of the US East Coast have anomalously cooled (Figure 19). There has been some anomalous warming in parts of the tropical Atlantic, but the changes in this region have been relatively small. A likely reason for these SST changes is a change in sign of the North Atlantic Oscillation (NAO) from positive to negative over the past several weeks, which has tended to favor the anomalous SST trends that have been observed (Figure 20).

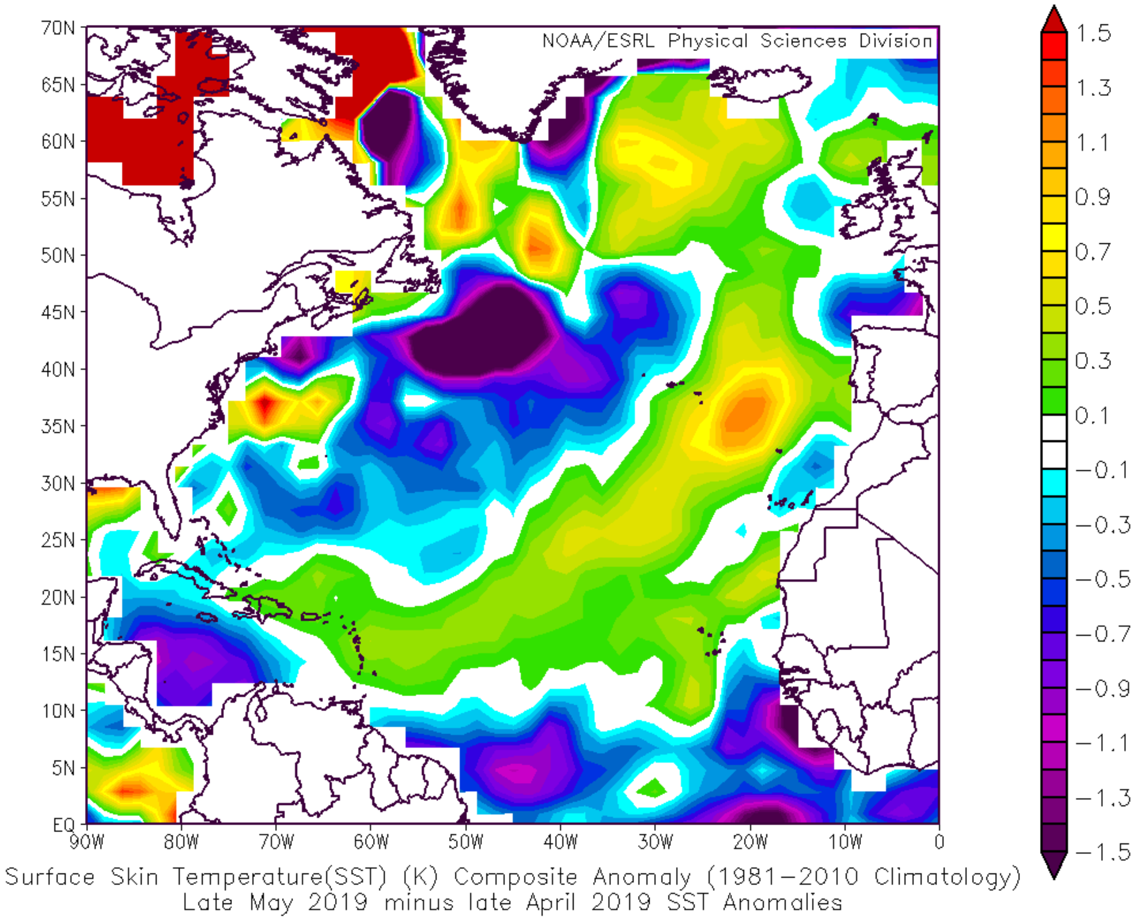

Figure 19: Late May 2019 minus late April 2019 SST anomalies.

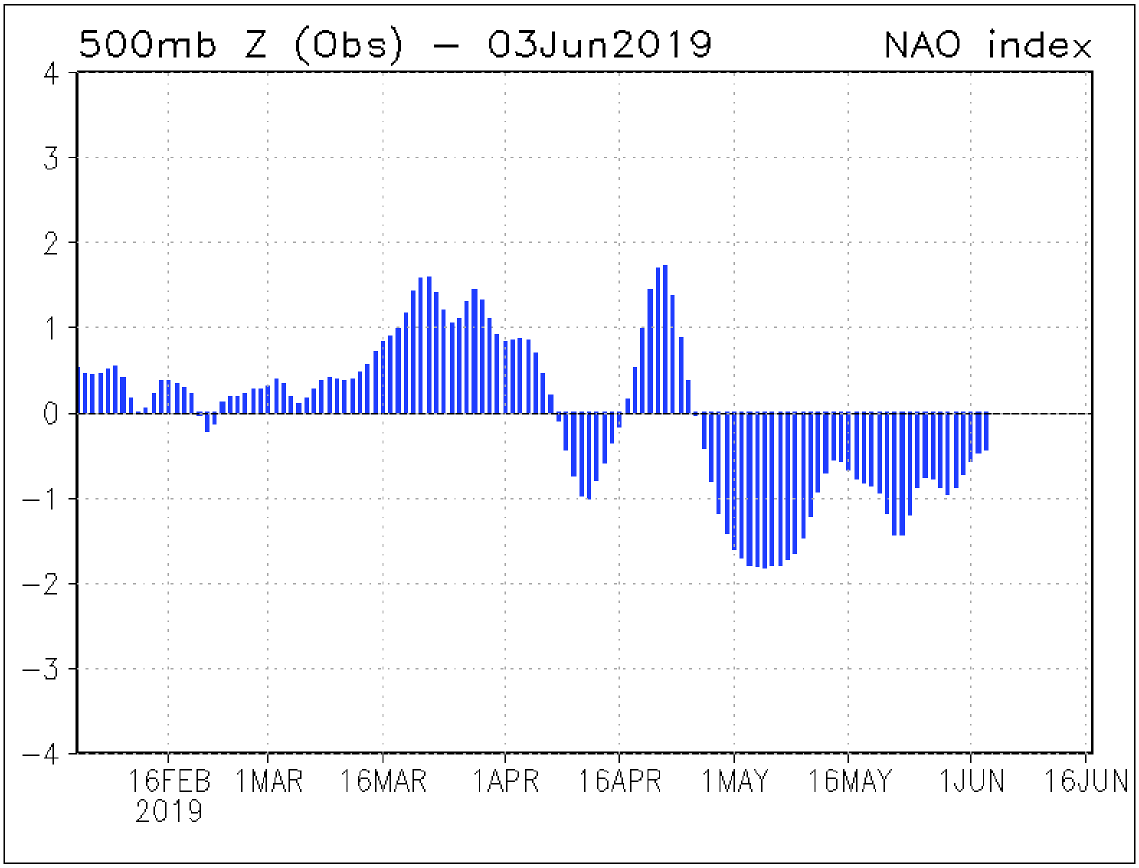

Figure 20: Observed standardized values of the daily NAO since February 2019. The NAO switched from being generally positive to being generally negative in late April.

While there is considerable uncertainty as to what Main Development Region SSTs (10-20°N, 60-20°W) will look like during August-October of 2019, current SST anomalies are slightly above the long-term average (~0.1°C) (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 May. Consequently, there is still large uncertainty as to what may occur by the peak of the Atlantic hurricane season given current MDR SST anomalies.

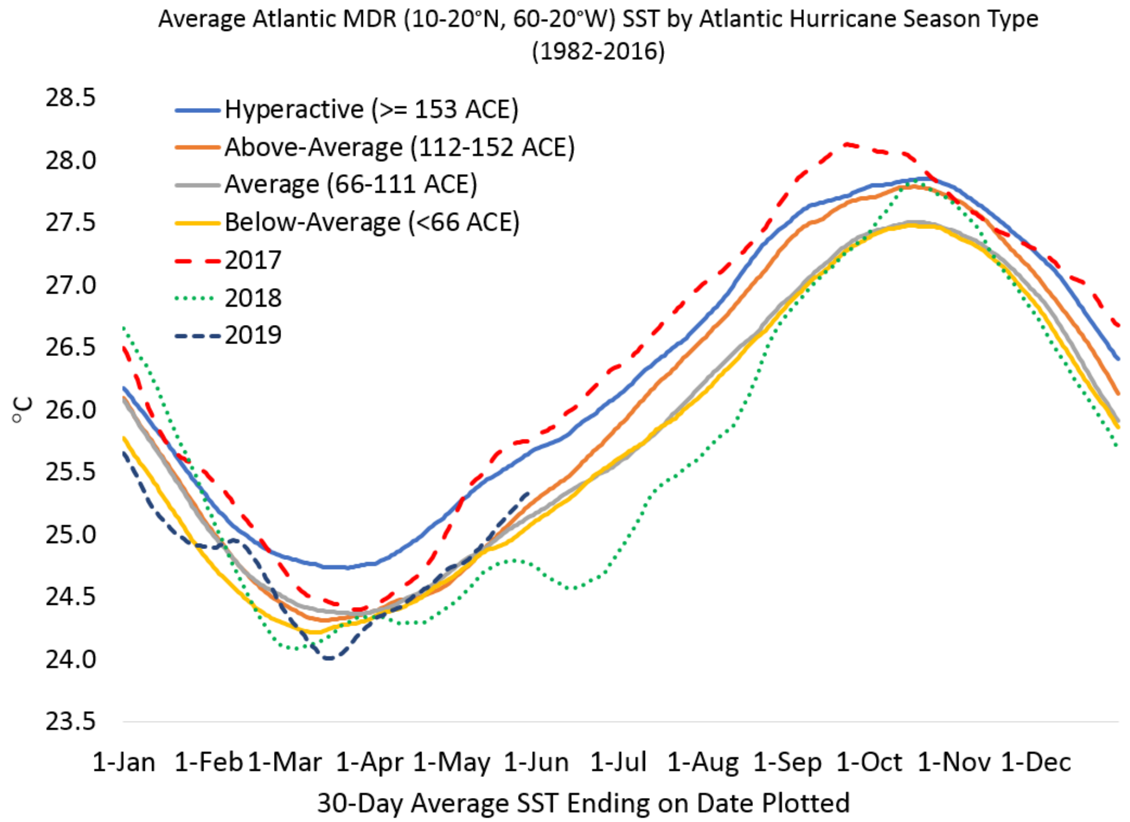

Figure 21: Tropical Atlantic SST anomalies plotted for the average of various Atlantic hurricane season types from 1982-2016. Also plotted are 30-day running averages of SSTs for 2017, 2018 and 2019. Note, however, that there is relatively little spread between below-average, average and above-average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

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 near its 1950-2000 average of 100, and therefore, landfall probabilities are near 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)	81% (79%)	69% (68%)	54% (52%)	86% (84%)	97% (97%)
Gulf Coast (Regions 1-4)	60% (59%)	44% (42%)	31% (30%)	62% (60%)	85% (83%)
Florida plus East Coast (Regions 5-11)	52% (50%)	46% (44%)	32% (31%)	63% (61%)	82% (81%)
Caribbean (10-20°N, 60-88°W)	84% (82%)	59% (57%)	44% (42%)	77% (75%)	96% (96%)

7 Summary

An analysis of a variety of different atmosphere and ocean measurements (through May) which are known to have long-period statistical relationships with the upcoming season's Atlantic tropical cyclone activity, as well as output from dynamical models, indicate that 2019 should have near-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 the North Atlantic 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 9 July and Monday 5 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